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(54) **SYSTEMS AND METHODS FOR ADDING OR SUBTRACTING ENERGY TO BODY MOTION**

(71) Applicants: **SpringActive, Inc.**, Tempe, AZ (US); **Arizona Board of Regents on behalf of Arizona State University**, Scottsdale, AZ (US)

(72) Inventors: **Thomas G. Sugar**, Tempe, AZ (US); **Jason Kerestes**, Summerville, SC (US); **Matthew A. Holgate**, Chandler, AZ (US); **Jeffrey A. Ward**, Phoenix, AZ (US); **Thierry Flaven**, Saint Pierre d'Allevard (FR)

(73) Assignees: **Arizona Board of Regents on Behalf of Arizona State University**, Scottsdale, AZ (US); **SpringActive, Inc.**, Tempe, AZ (US)

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Related U.S. Application Data

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(51) **Int. Cl.**
B25J 9/00 (2006.01)

(52) **U.S. Cl.**
CPC *B25J 9/0006* (2013.01); *Y10S 901/02* (2013.01)

(58) **Field of Classification Search**
CPC A61H 1/00; A61H 1/001–1/003; A61H 1/005; A61H 1/02; A61H 2001/0211; A61H 1/0214; A61H 1/0229; A61H 1/0237–1/0244; A61H 1/0262; A61H 1/0266–1/0296; A61H 3/00; A61H 2003/005; A61H 2003/007; A61H 3/008; A61H 2201/1657–2201/1659; A61H 2201/50; A61H 2201/5058; A61H 2201/5064; A61H 2201/5069; A61H 2201/5079; A61H 2201/5084; Y10S 901/02–901/04; Y10S 901/09; Y10S 901/46; Y10S 901/48; Y10S 901/50; B25J 9/0006; B25J 11/002; B25J 13/088; A63B 21/00–21/00003; A63B 21/00058; A63B 21/00181; A63B 21/00196; A63B 21/1403–21/1449; A63B 23/035; A63B 23/04; A63B 23/12; A63B 2230/62–2230/625; G05B 19/423; G05B 2219/40305; G05B 2219/39004; G05B 2219/40202; A61F 2002/704; A61F 2/72; A61F 2002/7615; A61F 2002/7625; A61F 2/60; A61F 2002/607–2002/608
USPC 700/250, 254, 256, 257, 258, 260–261, 700/264; 901/2–4, 9, 46, 48, 50; 318/568.13–568.14, 568.16, 568.22; 414/1–2
See application file for complete search history.

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Primary Examiner — Bao Long T Nguyen
(74) *Attorney, Agent, or Firm* — Robert D. Atkins; Patent Law Group: Atkins and Associates, P.C.

(57) **ABSTRACT**

A phase oscillating device for affecting movement of a limb or a primary body includes a sensor coupled to the primary body. A physical state of the primary body is measured using the sensor. A phase angle of the primary body is determined based on the physical state measurement. The physical state measurement includes position, velocity, or acceleration. The phase angle of the primary body is filtered using a sine function. An actuator is coupled to the primary body. The actuator is triggered based on the phase angle of the primary body to provide a force or torque to assist or resist movement of the primary body. A secondary body is coupled to the primary body. The secondary body is oscillated using the actuator, which is triggered in phase with a gait step. Alternatively, a fan is coupled to the primary body and actuator to provide the oscillating force.

31 Claims, 24 Drawing Sheets
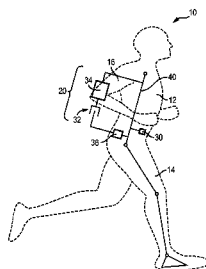
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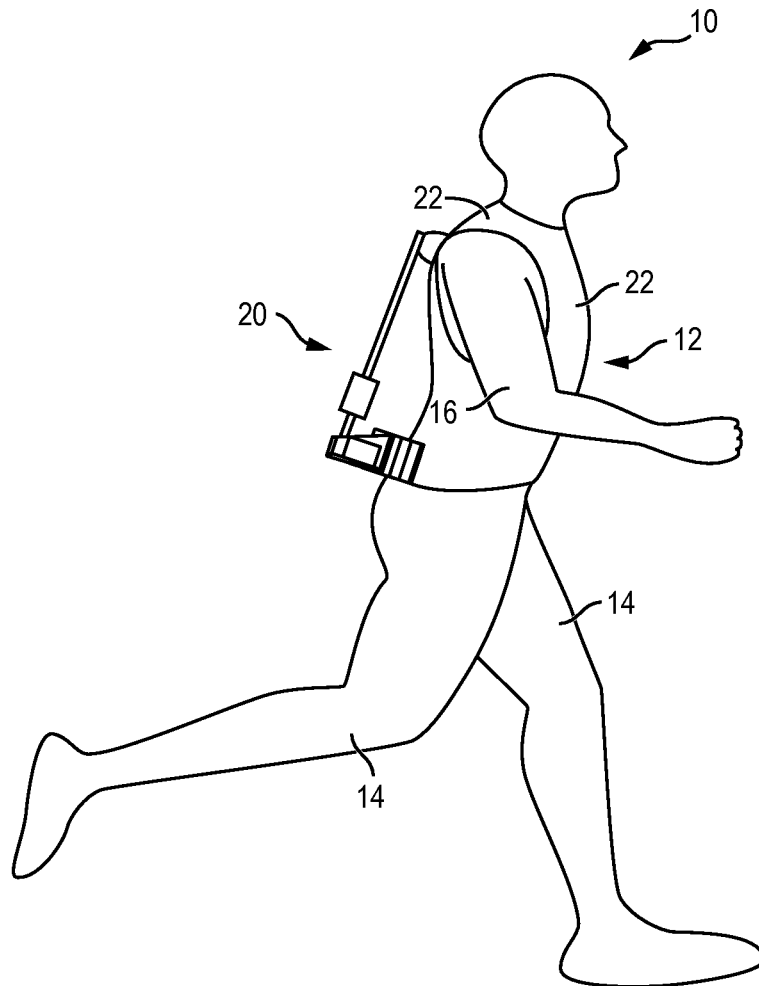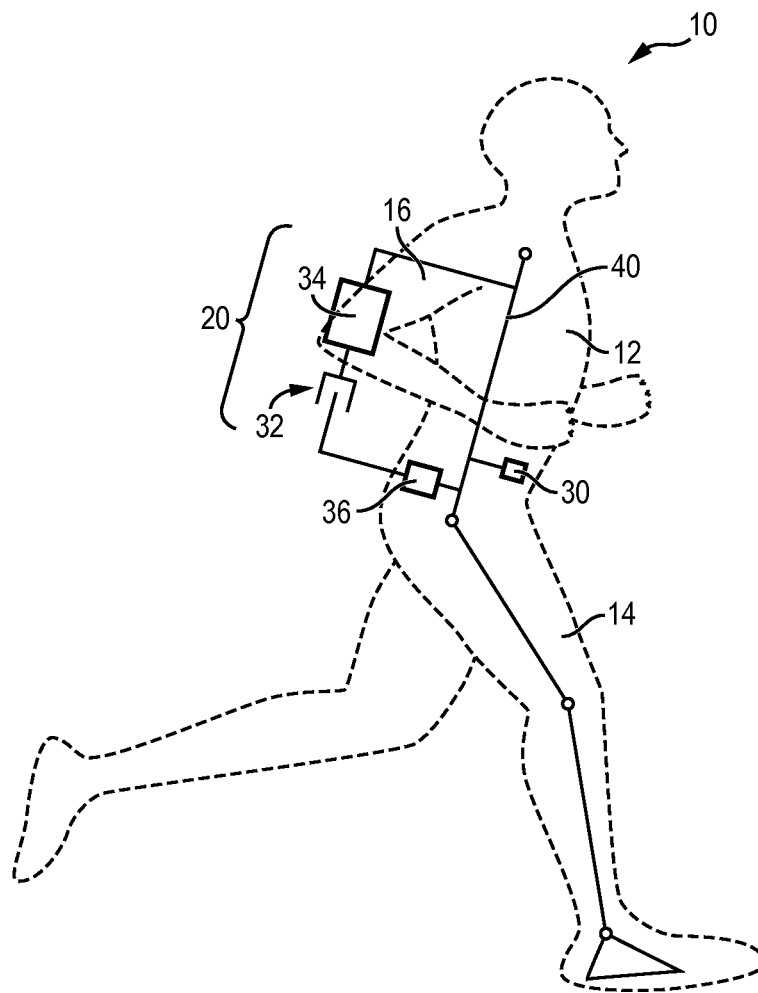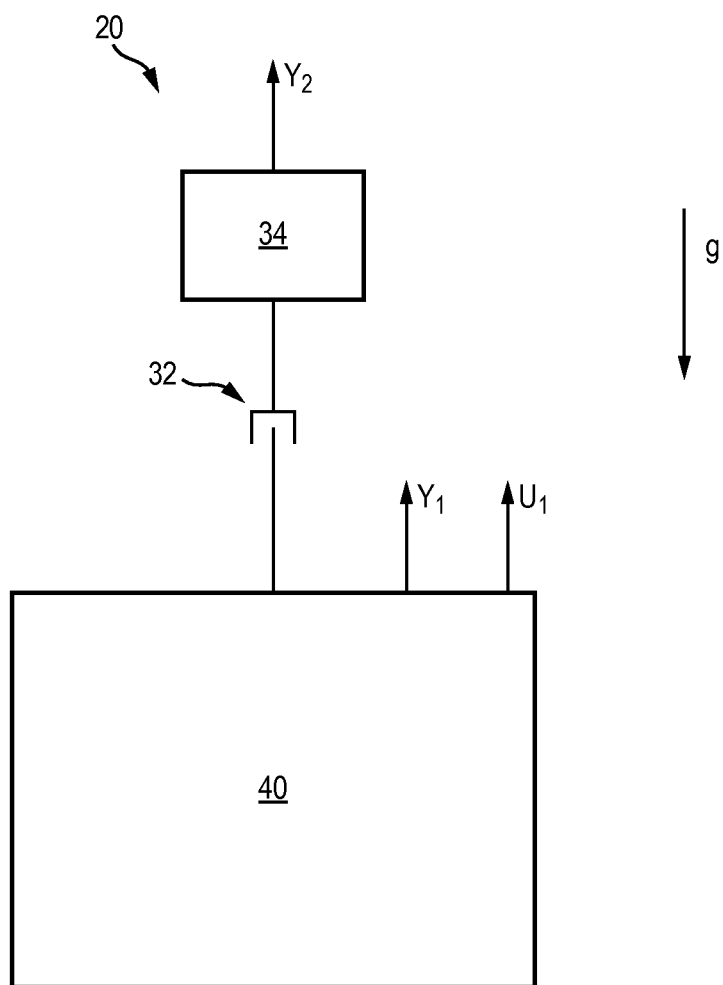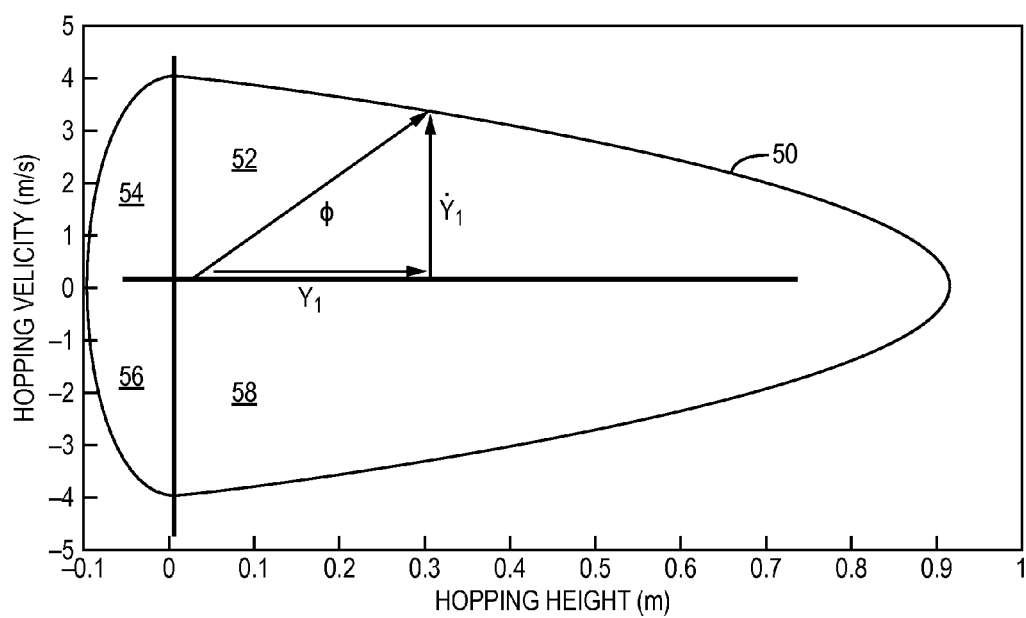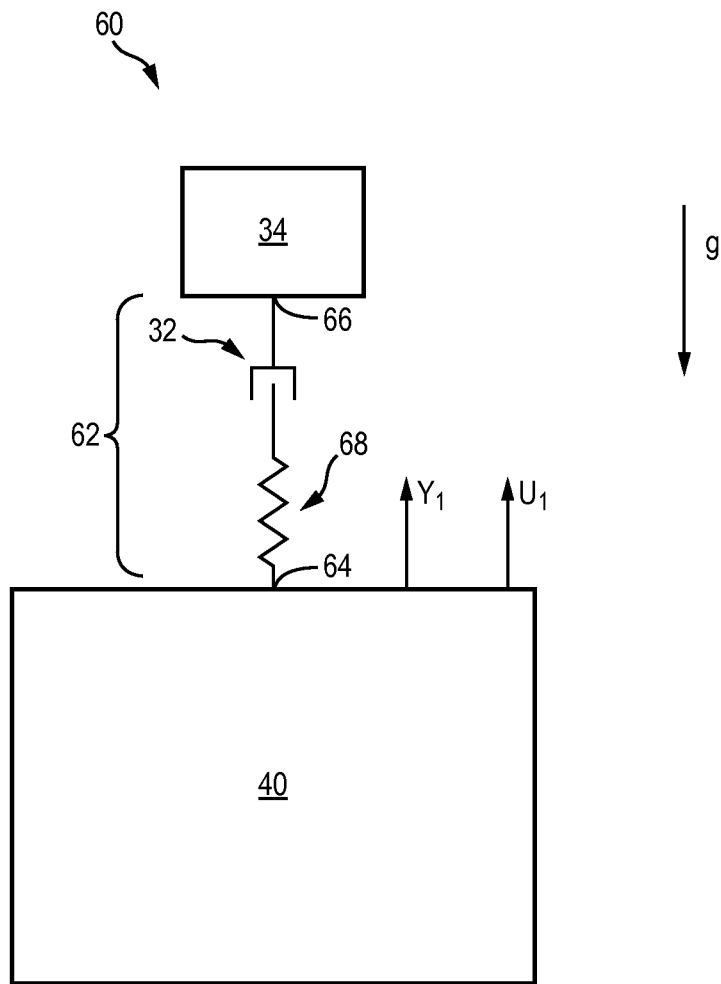
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FIG. 1a

FIG. 1b

FIG. 1c

FIG. 1d

FIG. 1e
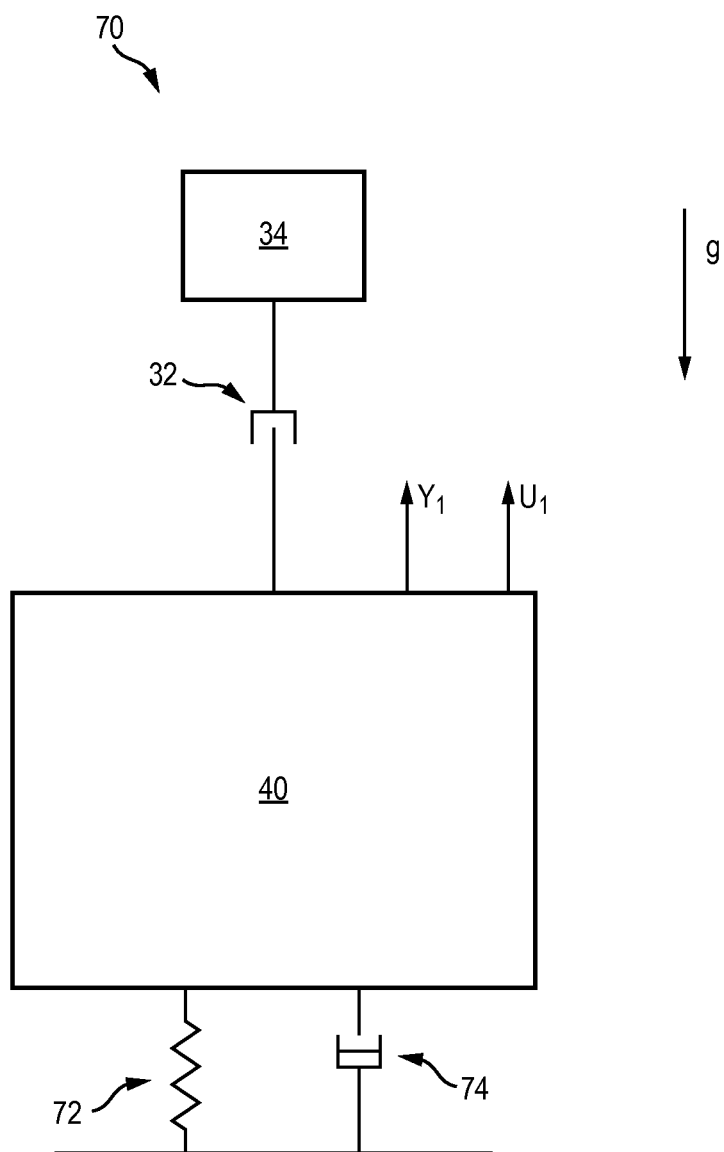
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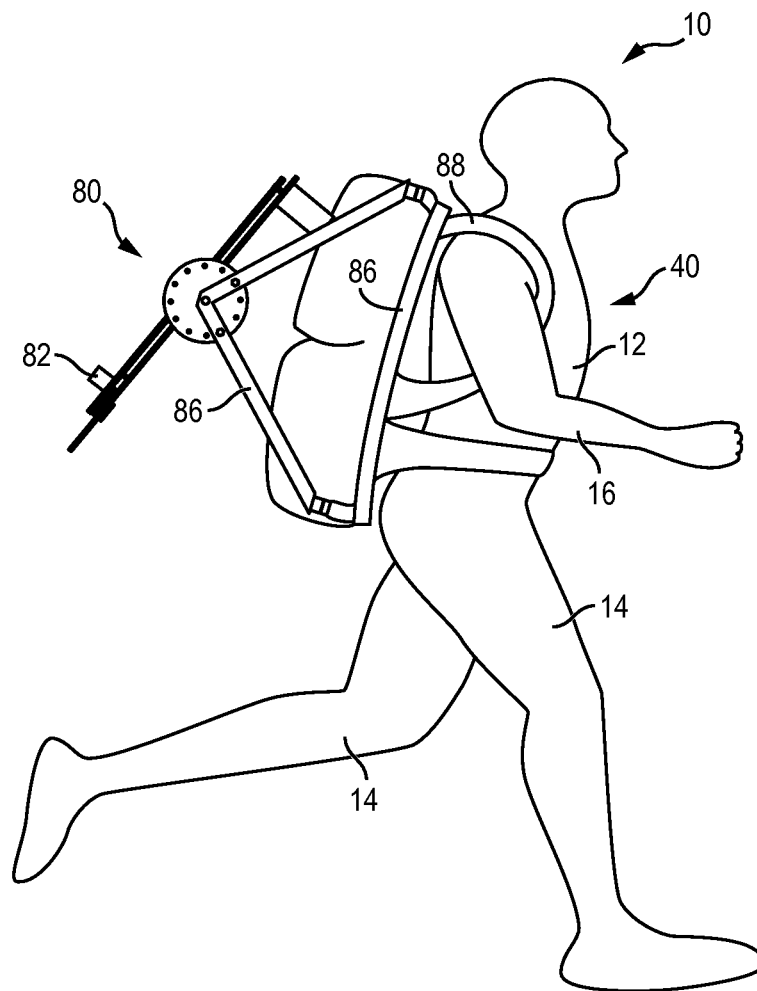
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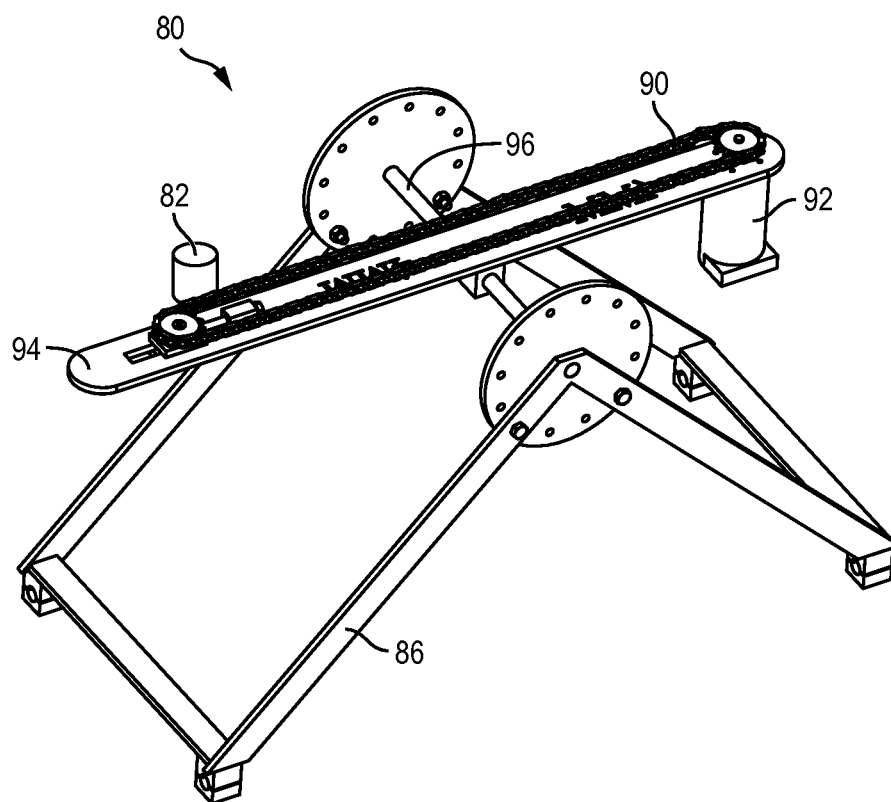
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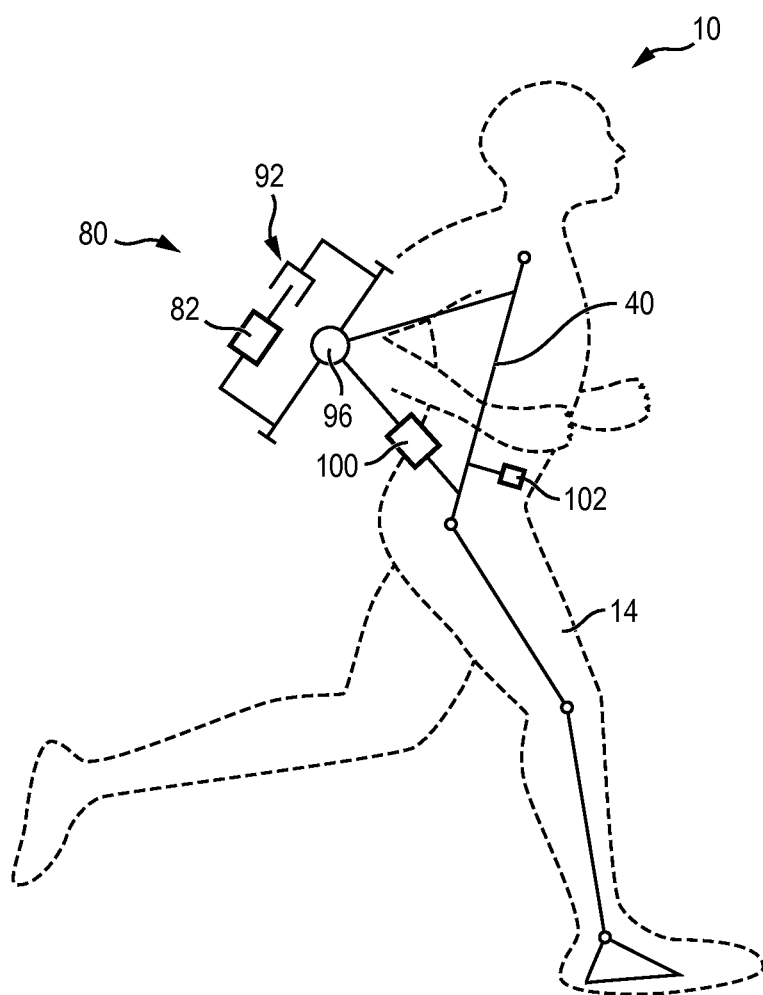
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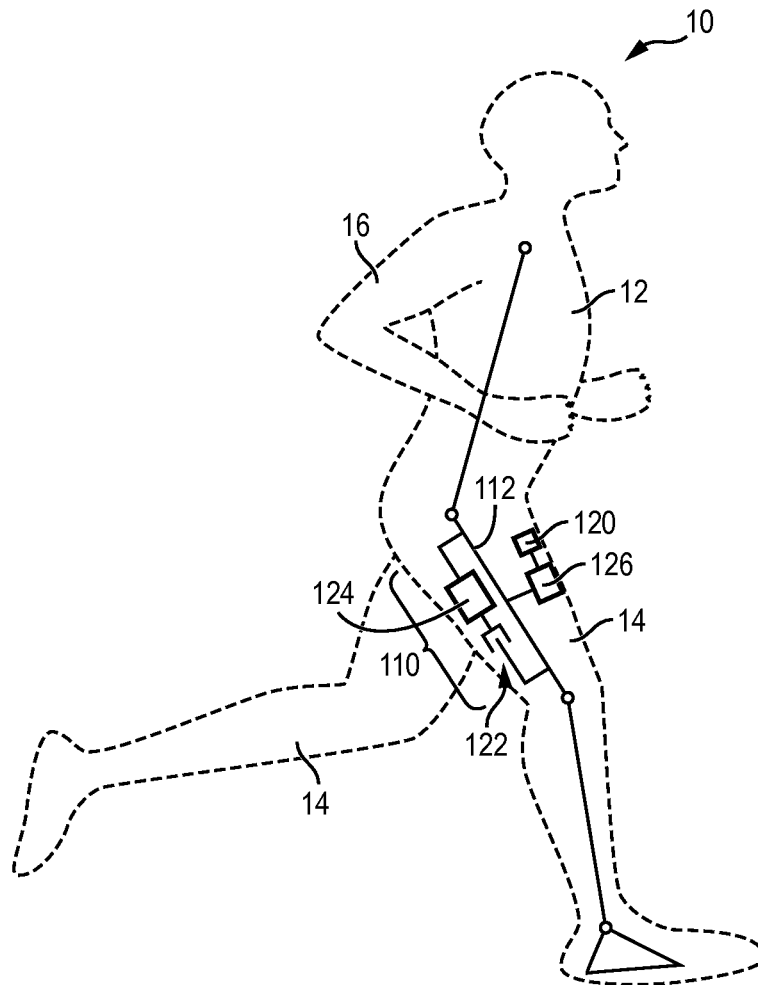
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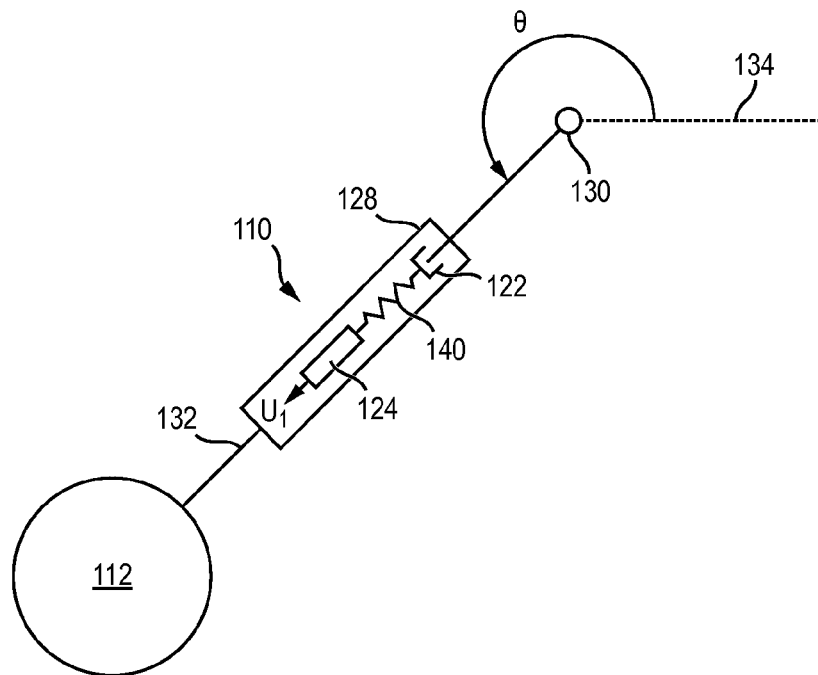
FIG. 3b

FIG. 3c

FIG. 4a
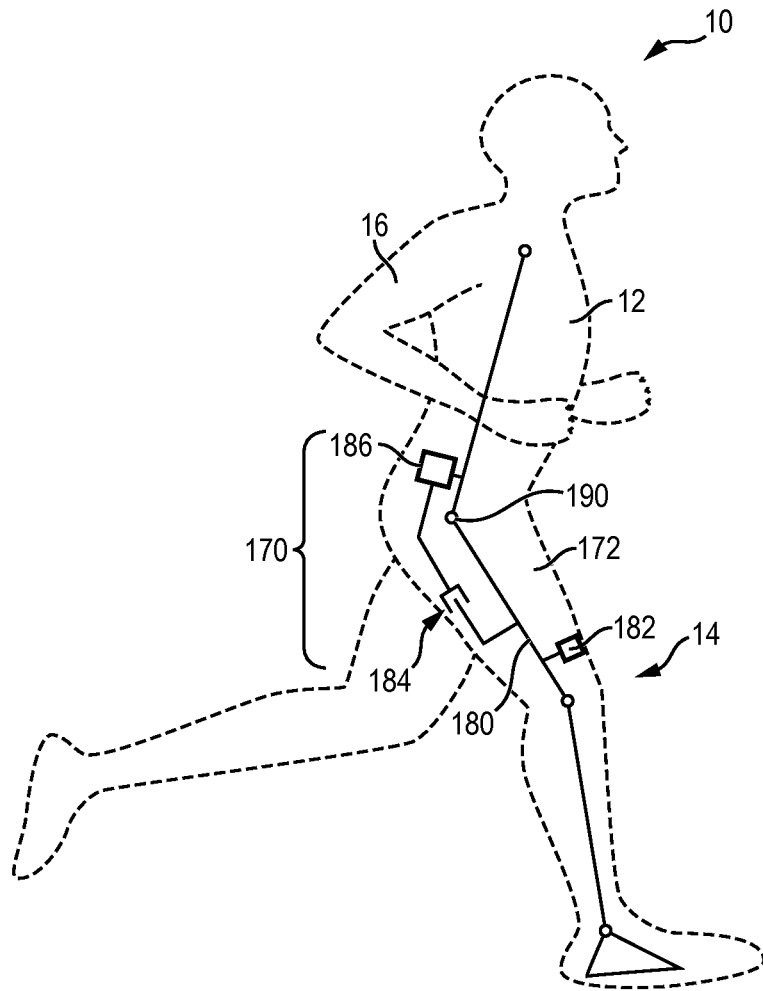
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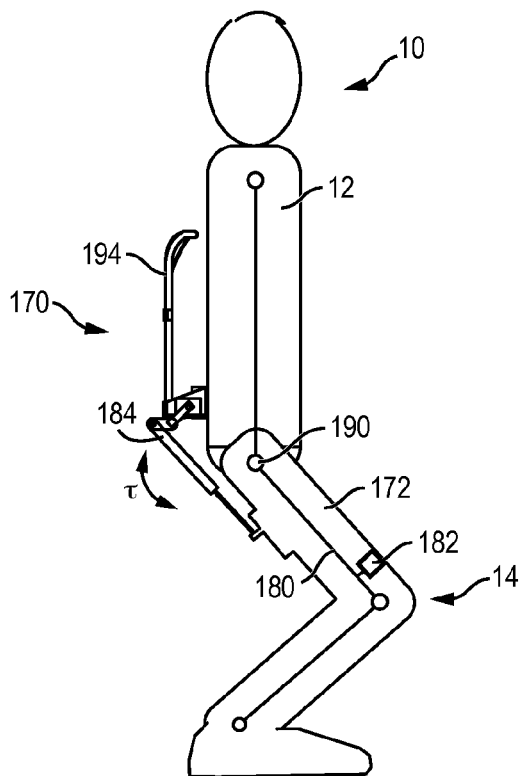
FIG. 4c
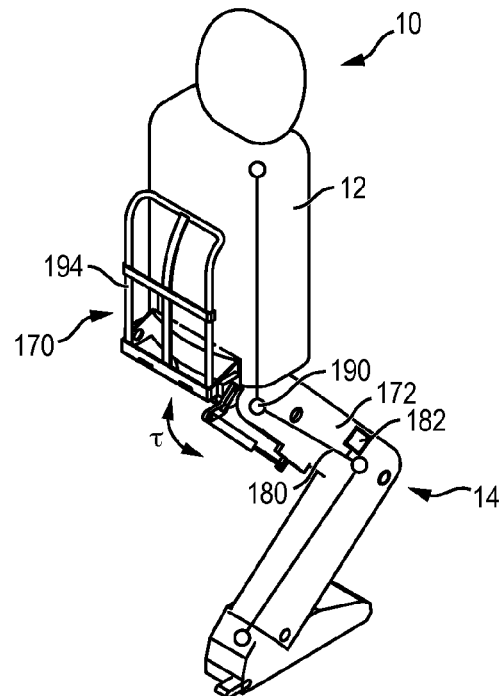
FIG. 4d
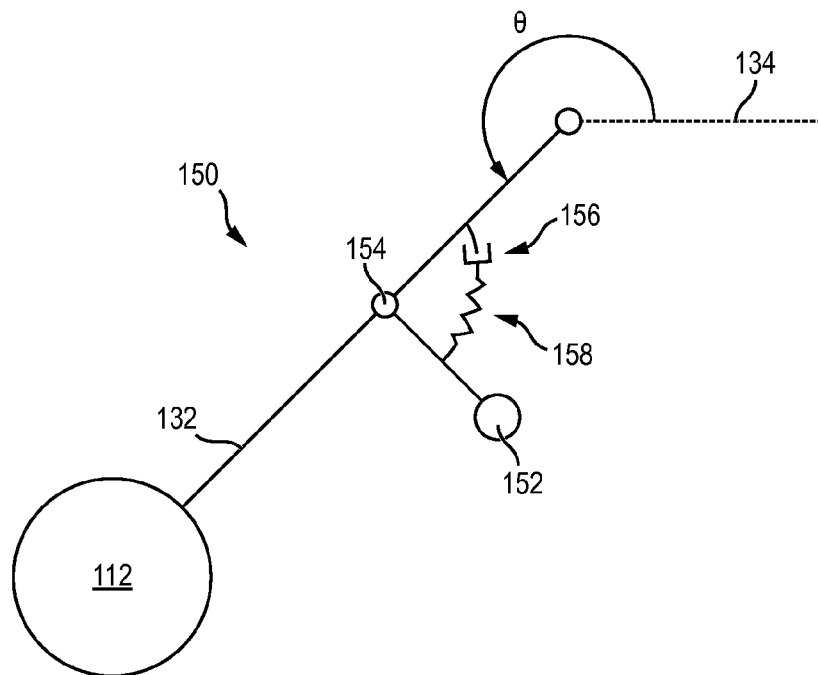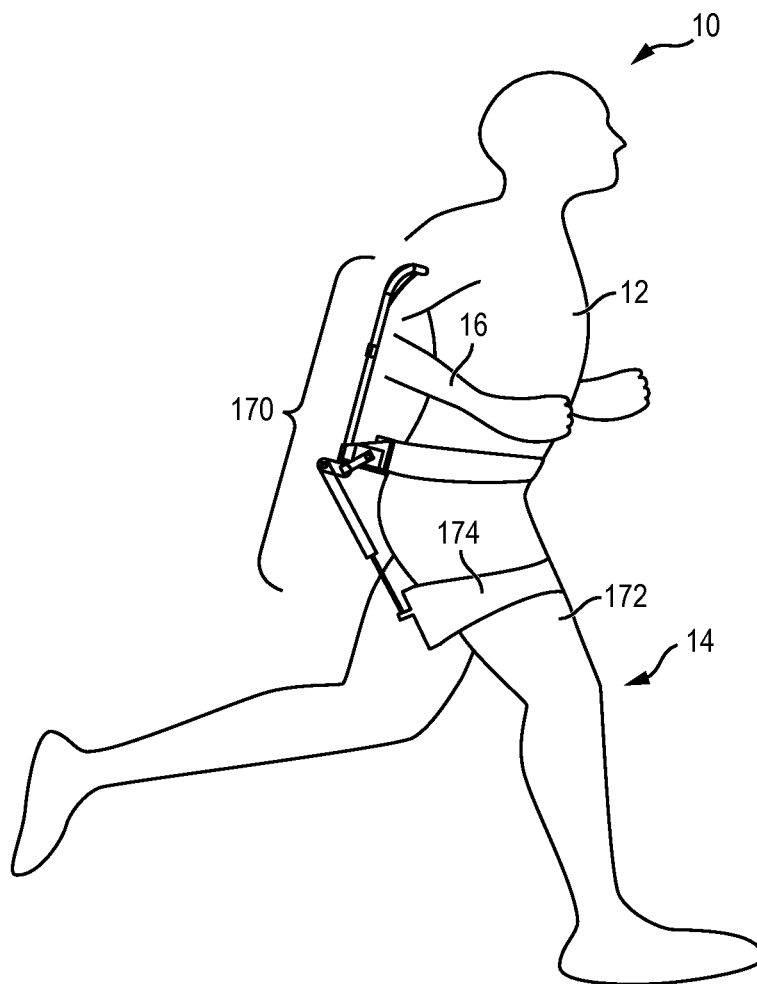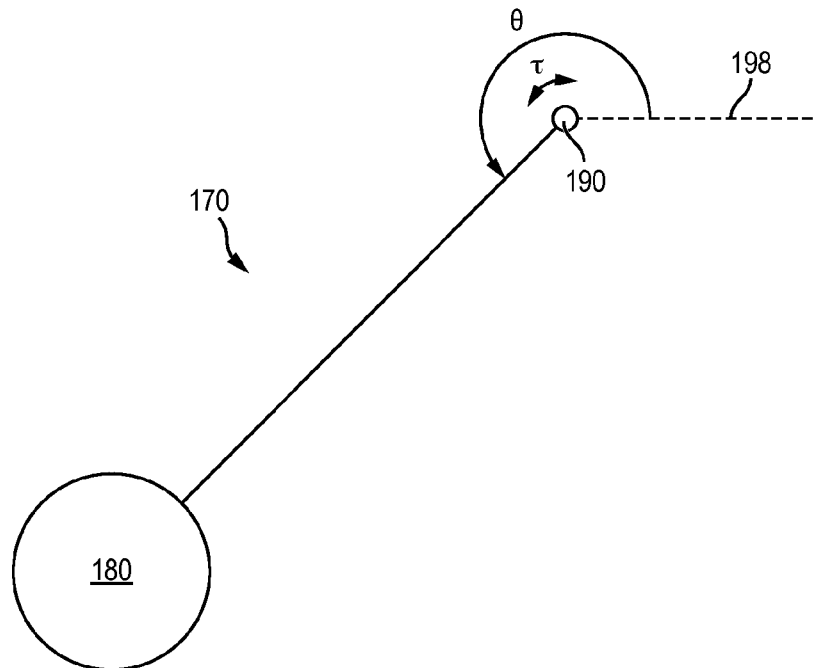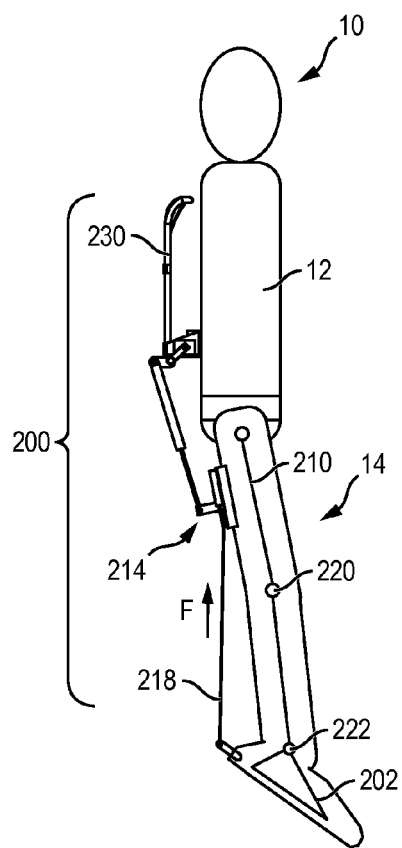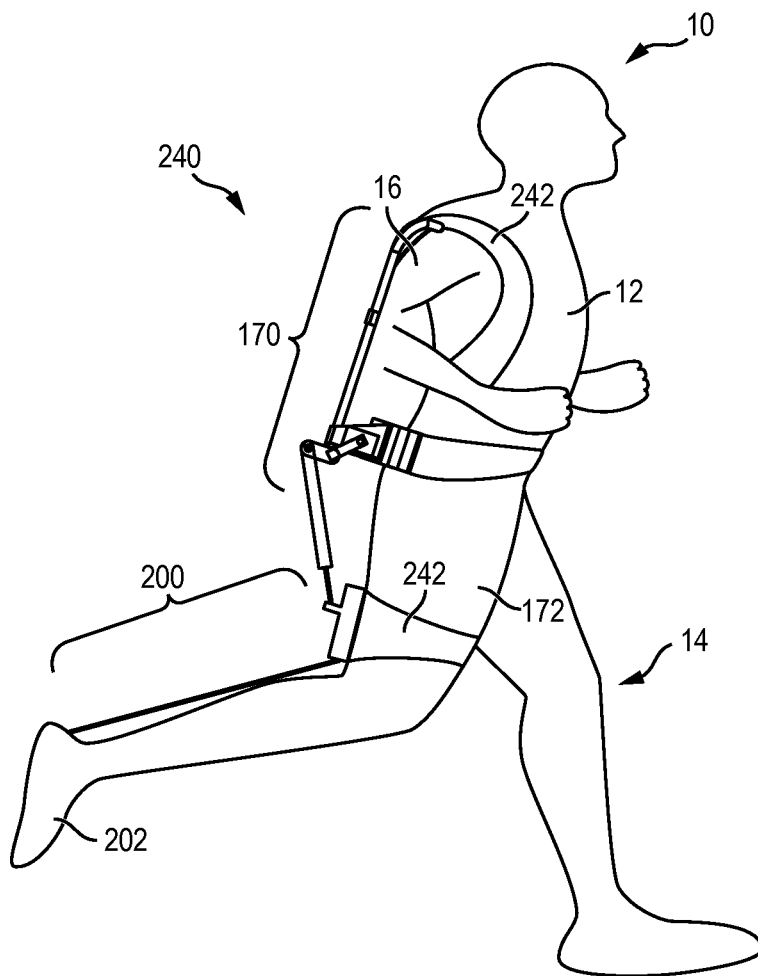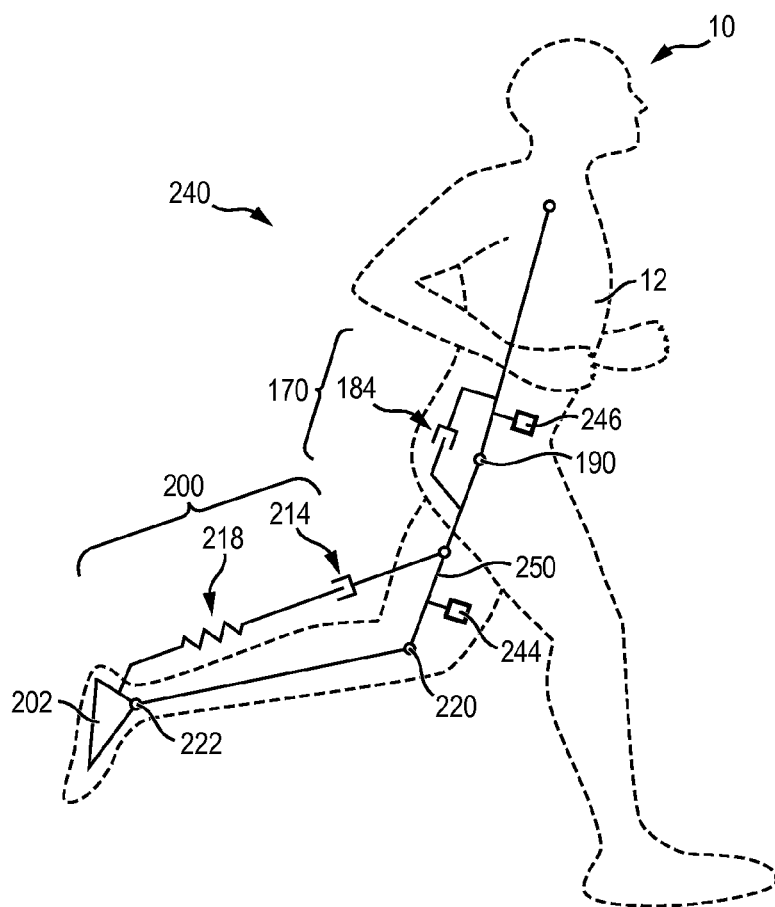
FIG. 4e
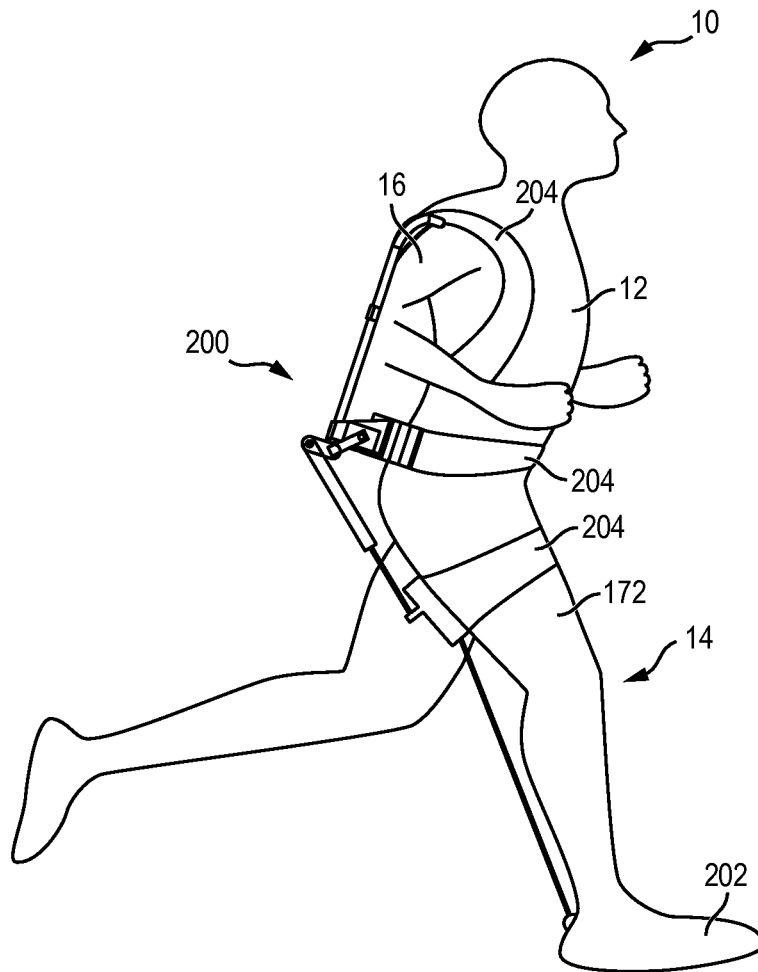
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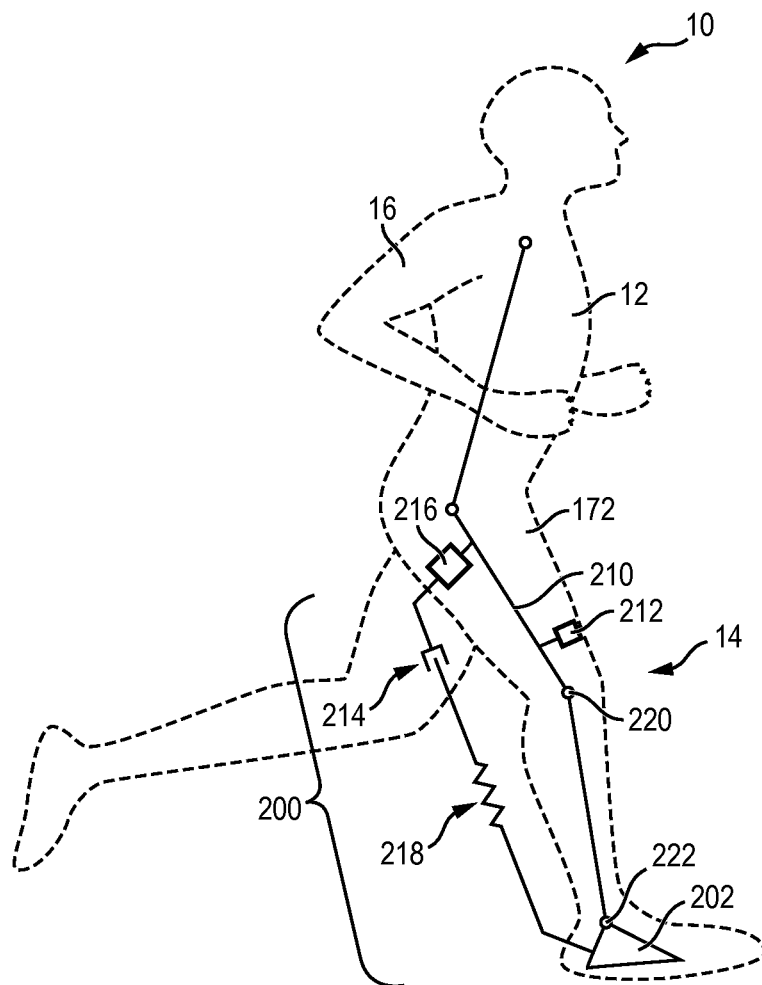
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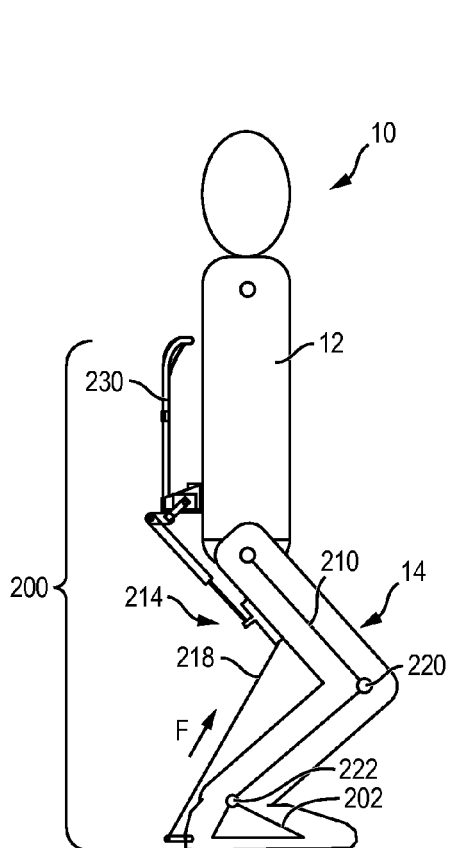
FIG. 5c

FIG. 5d

FIG. 6a

FIG. 6b

FIG. 6c

FIG. 7a

FIG. 7b

310

312

314

304

306

10

302

FIG. 8a

322

312

304

320

324

302

FIG. 8b

310

330

312 ← Y₂

Y₁ ← 304

FIG. 8c

340

330   342

312 ← Y₂

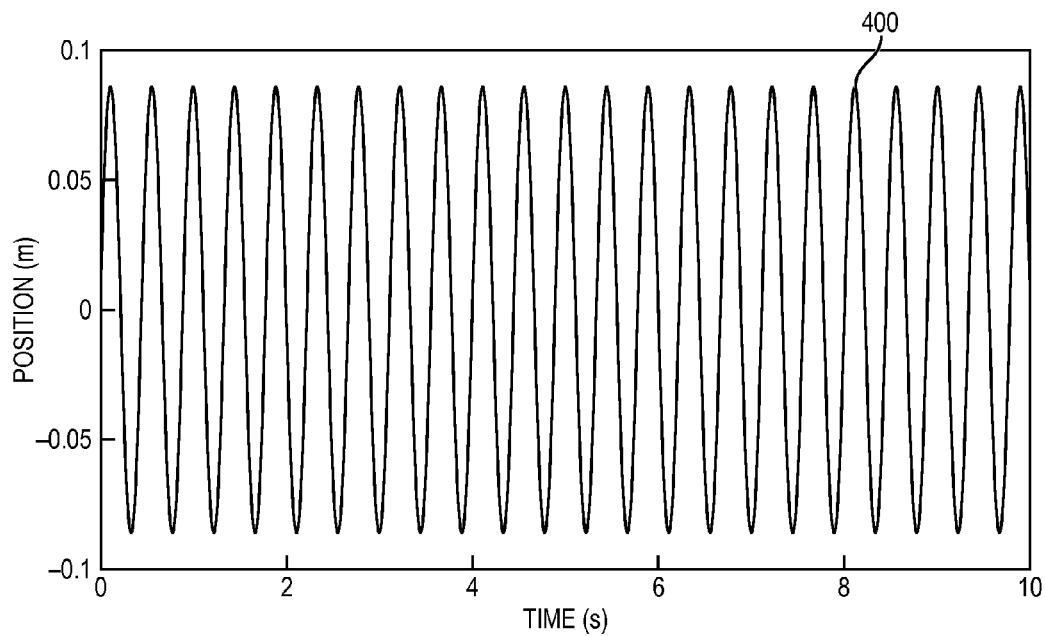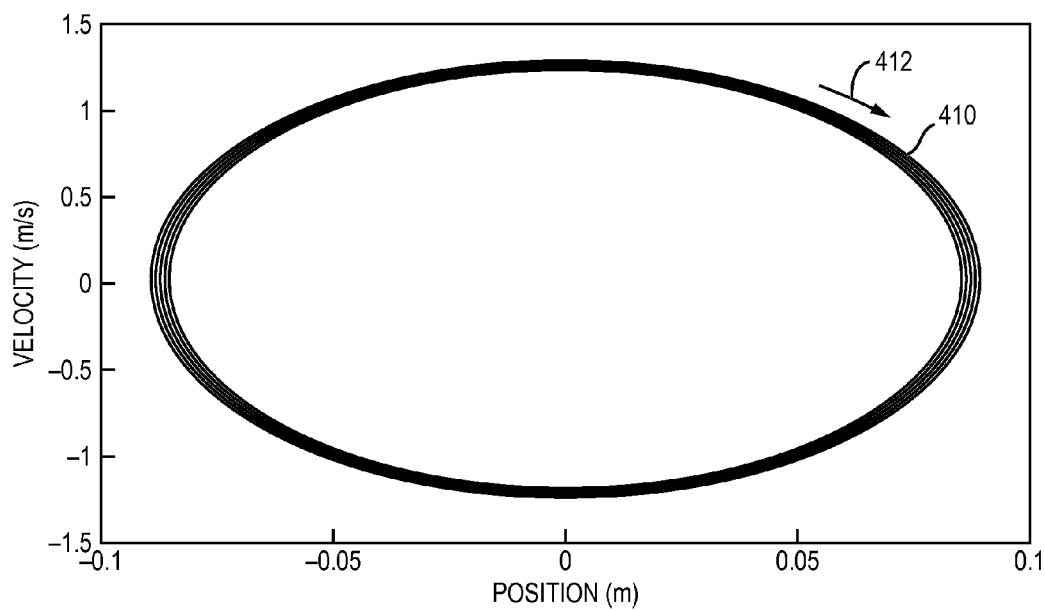Y₁ ← 304
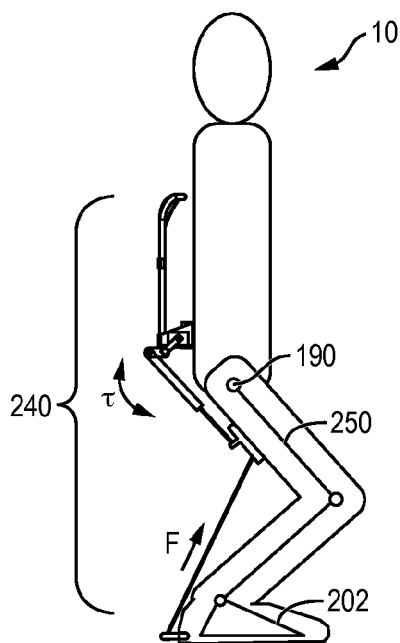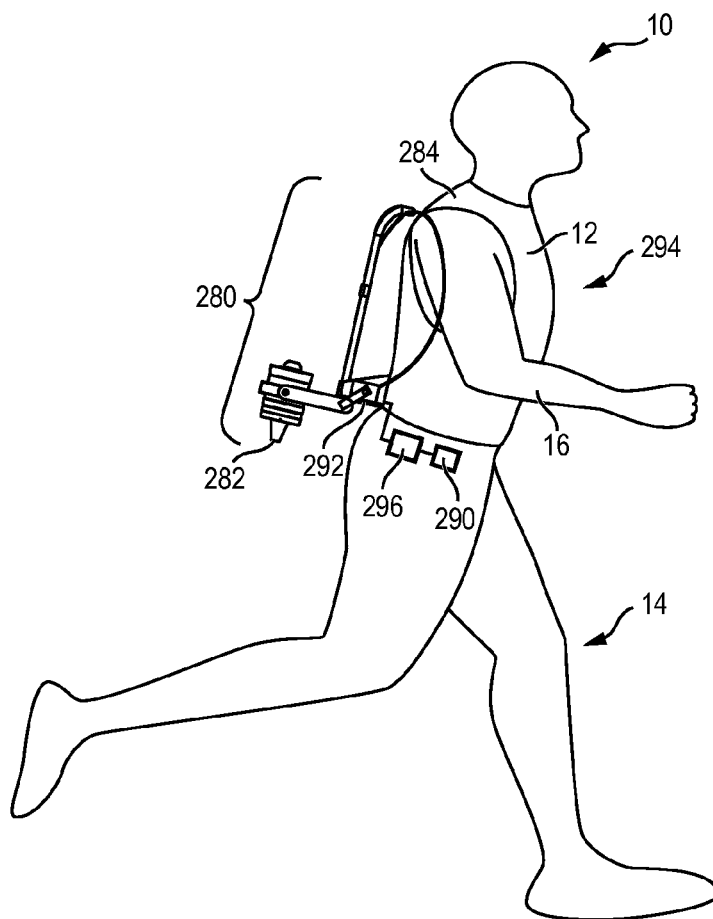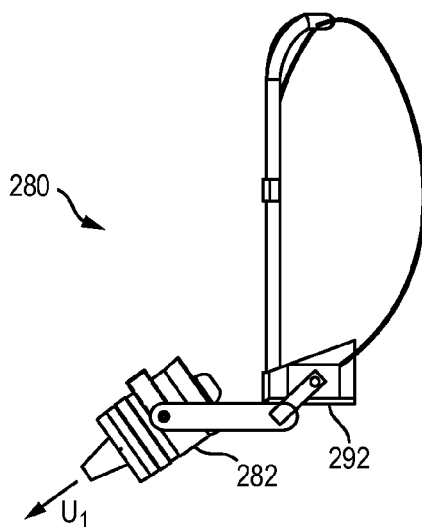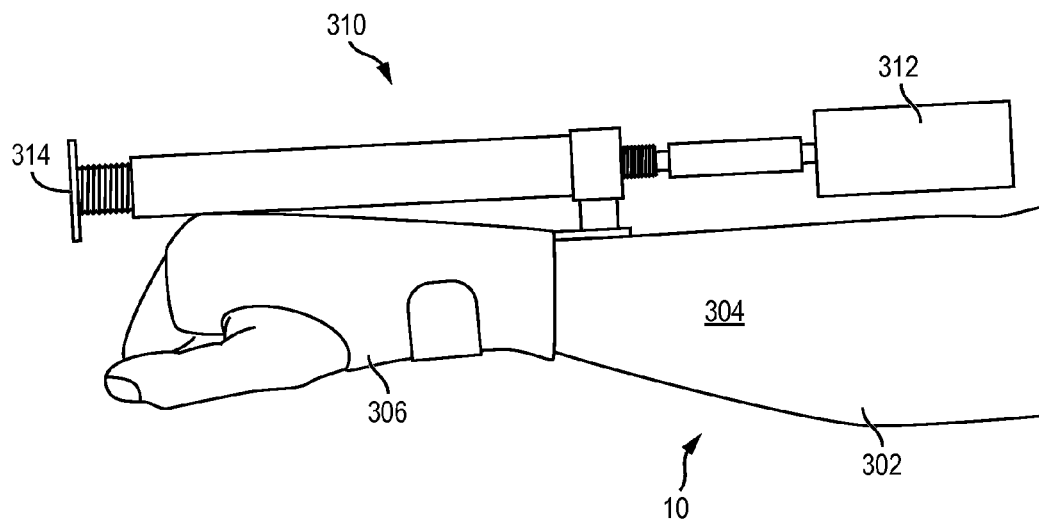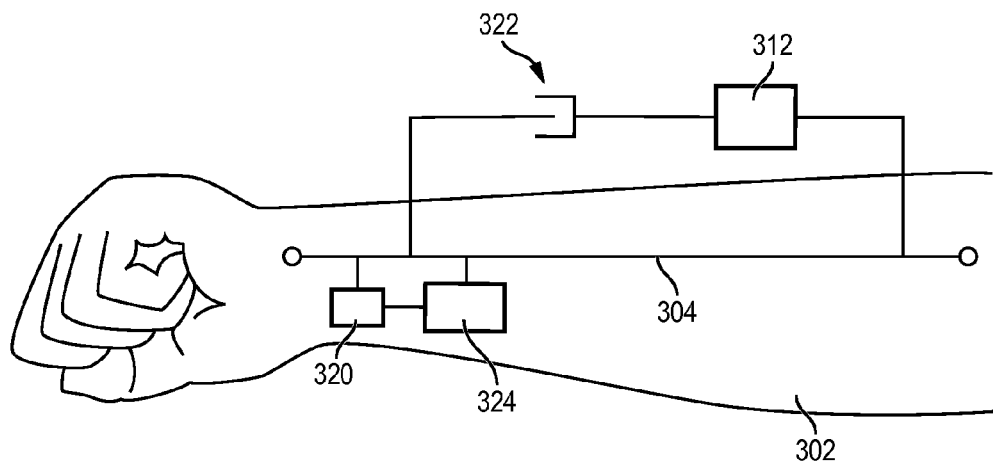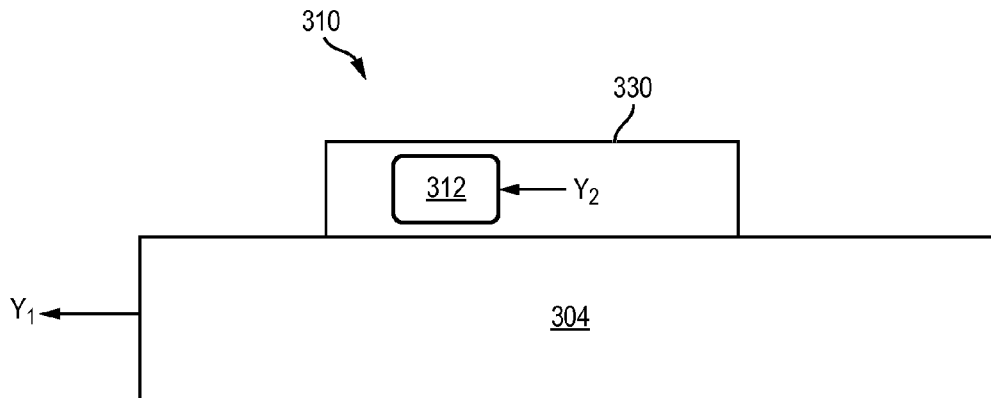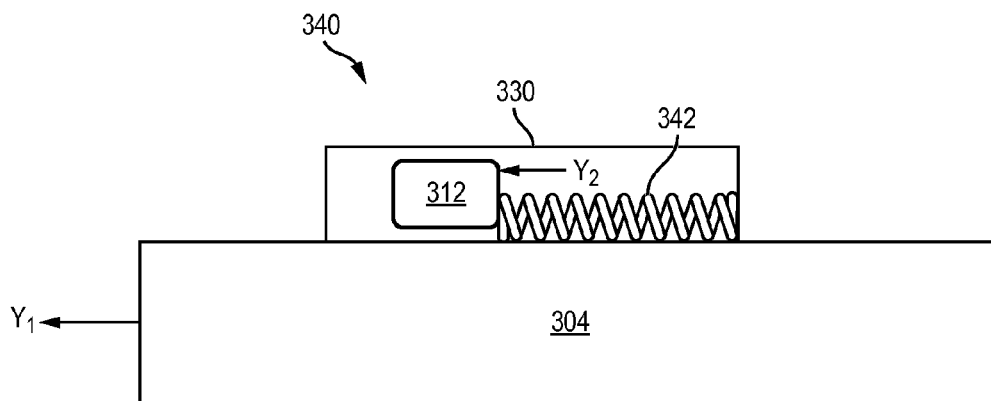
FIG. 8d

FIG. 9a
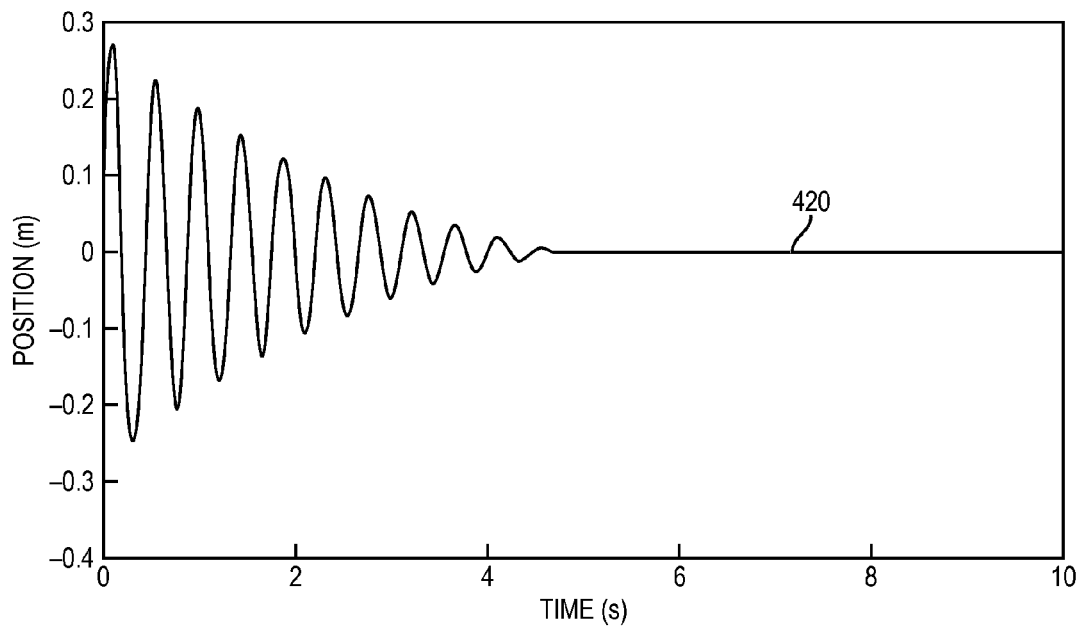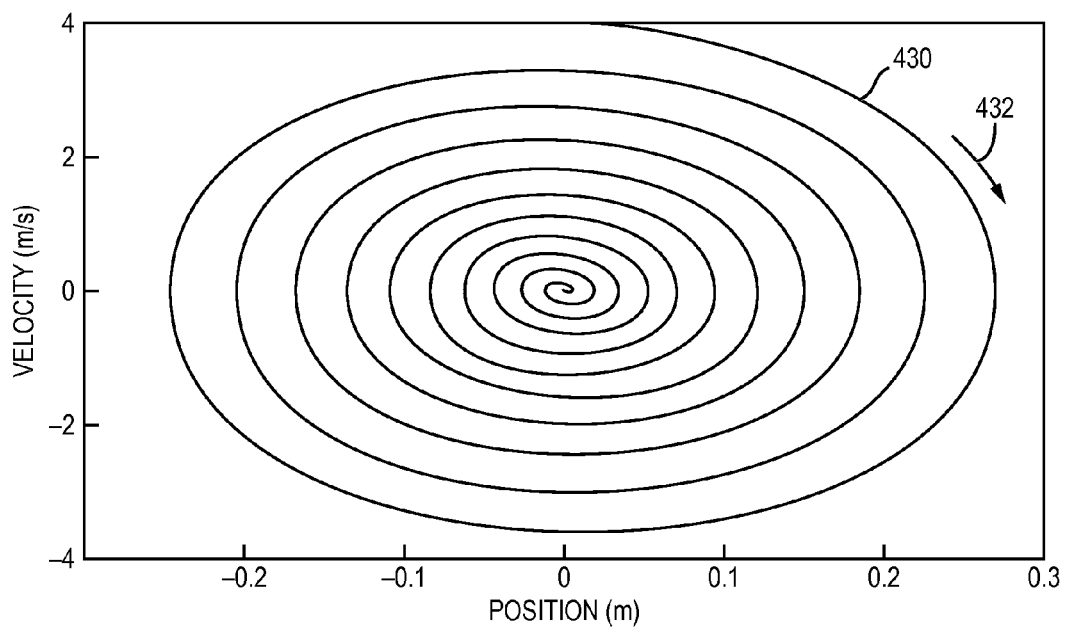

FIG. 9b

FIG. 9c

FIG. 9d

SYSTEMS AND METHODS FOR ADDING OR SUBTRACTING ENERGY TO BODY MOTION

CLAIM TO DOMESTIC PRIORITY

The present application claims the benefit of U.S. Provisional Application No. 61/753,199, filed Jan. 16, 2013, and U.S. Provisional Application No. 61/871,571, filed Aug. 29, 2013, which applications are incorporated herein by reference.

FEDERALLY-SPONSORED RESEARCH OR DEVELOPMENT

The present invention was made with government support under grant number W911QX-12-1-0002, awarded by the Army Research Labs. The government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates in general to prosthetic, orthotic, robotic, and exoskeleton devices and, more particularly, to oscillating mechanisms for adding or subtracting energy to motion of a body.

BACKGROUND OF THE INVENTION

Human locomotion, such as walking and running, is commonly described in terms of gait. Gait is a cyclical pattern of leg and foot movement that creates locomotion. A gait cycle is defined for a single leg and begins with the initial contact of the foot with the ground or heel strike. The conclusion of a gait cycle occurs when the same foot makes a second heel strike. The gait cycle can be divided into two phases, stance phase and swing phase. Stance phase begins with heel strike and ends when the toe of the same foot leaves the ground. Swing phase begins when the foot leaves contact with the ground and ends with heel strike of the same foot.

Prosthetic and orthotic devices help restore mobility to people who lack able-bodied motion or gait. Prosthetic devices are intended to replace the function or appearance of a missing limb and can return mobility to the wearer or user. Orthotic devices are intended to support or supplement an existing limb, by assisting with movement, reducing weight-bearing loads on the body, reducing pain, and controlling or restricting movement. Prosthetic and orthotic devices are available to replace or support various portions of the body. One goal of lower limb prosthetic and orthotic devices is to help the user achieve a normal gait while reducing energy expended by the user.

Individuals have unique gait patterns. Energy or metabolic expenditure during an individual's gait depends on several factors including, body mass, stride length, step rate, and other physical and environmental factors. Individuals have physical and metabolic limits, which determine the speed and distance an individual can travel on foot. Other forces hindering human gait are air drag and rolling friction. Decreasing the metabolic cost for an individual's gait allows the individual to run faster or travel for a longer distance while minimizing the energy expended by the individual.

Over-speed running and training is a method of reducing metabolic cost for gait. Using pulley systems and springs, two runners are coupled together to reduced metabolic cost when one runner pulls another. When an external, horizontal force is added to a runner on a treadmill, the force reduces the positive horizontal ground reaction force needed for push-off.

The force increases the negative horizontal ground reaction force at landing which increases braking forces. However, attaching a pulley system to an individual to assist with gait leaves the individual tethered to the treadmill or to another runner. Negative damping has also been used to create an external force in the same direction as a velocity of the body by adding positive power. However, negative damping can cause an unstable amount of energy added as velocity increases.

SUMMARY OF THE INVENTION

A need exists for a wearable device that enhances motion and reduces metabolic output during activities. Accordingly, in one embodiment, the present invention is a method of making a movement assistance device comprising the steps of providing a sensor, measuring a physical state of a limb using the sensor, determining a phase angle of the limb based on the physical state, coupling an actuator to the limb, and triggering the actuator based on the phase angle of the limb to provide a force to assist movement of the limb.

In another embodiment, the present invention is a method of making a phase oscillating device comprising the steps of providing a sensor, measuring a physical state of a primary body using the sensor, determining a phase angle of the primary body based on the physical state, and triggering an actuator based on the phase angle of the primary body to oscillate a force or torque applied to the primary body.

In another embodiment, the present invention is a movement assistance device comprising a primary body and a sensor coupled to the primary body to measure a physical state of the primary body. A controller is coupled to the sensor to determine a phase angle based on a physical state of the primary body. A secondary body is coupled to the primary body. An actuator is coupled to the controller and secondary body to move the secondary body based on the phase angle of the primary body.

In another embodiment, the present invention is a phase oscillating device comprising a primary body and a sensor coupled to the primary body. A controller is coupled to the sensor to determine a phase angle of the primary body. An actuator is coupled to the controller to oscillate a signal to the actuator based on the phase angle of the primary body.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1*a*-1*f* illustrate a wearable phase oscillating system;

FIGS. 2*a*-2*c* illustrate an alternative wearable phase oscillating system;

FIGS. 3*a*-3*c* illustrate a phase oscillating system worn on a limb of a user;

FIGS. 4*a*-4*e* illustrate a phase oscillating system worn on the hip of a user;

FIGS. 5*a*-5*d* illustrate a biarticular phase oscillating system worn on the legs of a user;

FIGS. 6*a*-6*c* illustrate a combination phase oscillating system;

FIGS. 7*a*-7*b* illustrate a phase oscillating system including a ducted fan;

FIGS. 8*a*-8*d* illustrate a phase oscillating system worn on an arm of a user; and

FIGS. 9*a*-9*d* illustrate graphical representations of the operation of a phase oscillating system.

DETAILED DESCRIPTION OF THE DRAWINGS

The present invention is described in one or more embodiments in the following description with reference to the fig-

ures, in which like numerals represent the same or similar elements. While the invention is described in terms of the best mode for achieving the invention's objectives, it will be appreciated by those skilled in the art that it is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims and their equivalents as supported by the following disclosure and drawings.

Muscles, ligaments, and tendons of the human body facilitate motion of limbs and locomotion of the body. The human body can be described as a mass-spring-damper system with the mass of the torso mounted on spring-damper-based legs. Adding energy into the human mass-spring-damper system at correct timing enhances oscillations of the human system during motion or gait. A small addition of energy results in a large resonance response. For example, a small oscillating mass coupled to the human body adds positive power to the hopping motion during the toe off phase of the gait cycle. The additional power during the toe off phase of gait enhances the hop height response of the human body. An oscillating mass that moves based on the phase angle of the human body adds positive power to the hopping motion during the toe off phase of the gait cycle. Alternatively, the oscillating mass is controlled to oscillate out of phase with the gait cycle in order to decrease or subtract power from motion of the body. When the oscillating mass is moved in an anti-phase motion, the hop height is decreased and a resistance training device or motion absorber is created. Therefore, the wearable powered phase oscillating systems described herein incorporate an oscillating mass or periodic external force or torque to increase or decrease the power available during motion of a body or limb.

FIGS. 1a-1f show a wearable powered phase oscillating system. FIG. 1a shows a wearable powered phase oscillating system worn on a torso of a user. User 10 has torso 12, lower limbs 14, and upper limbs 16. User 10 wears a phase oscillating system 20 in order to increase or decrease the available power during movement of user 10, for example, during gait or other activities. Phase oscillating system 20 senses motion of the human body and responds by adding a negative or a positive external force.

Phase oscillating system 20 is a device that oscillates a secondary mass, which applies an external force to a primary body. The external forces created by phase oscillating system 20 act on user 10, the primary body. User 10 is the primary body in phase oscillating system 20. The force applied to user 10 by phase oscillating system 20 increases or decreases the power of the user's motion. User 10 wears phase oscillating system 20, or phase oscillating system 20 is coupled to the user by an attachment system 22. In one embodiment, attachment system 22 includes straps, which are secured to torso 12 of user 10. In another embodiment, attachment system 22 includes straps, which secure phase oscillating system 20 to an upper limb 16 or a lower limb 14 of user 10. In yet another embodiment, phase oscillating system 20 is coupled to an exoskeleton or frame, which is coupled to user 10 or worn by user 10. In another embodiment, phase oscillating system 20 is incorporated into a backpack.

FIG. 1b shows a schematic representation of phase oscillating system 20 worn on torso 12 of user 10. Phase oscillating system 20 includes a sensor 30, an actuator 32, a secondary body 34, and a controller 36. Phase oscillating system 20 is attached to primary body 40. Phase oscillating system 20 operates by oscillating secondary body 34 with respect to primary body 40. Primary body 40 may be torso 12, lower limbs 14, and upper limbs 16, or other body portion of user 10. Primary body 40 is a human, animal, robot, or other object. In one embodiment, torso 12 represents primary body 40.

Phase oscillating system 20 includes a sensor 30 coupled to user 10. Sensor 30 is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, or other sensor. Sensor 30 measures a physical state of a primary body 40. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement. Primary body 40 can be a portion of user 10, such as the torso 12, lower limbs 14, and upper limbs 16, or other body portion of user 10. In one embodiment, sensor 30 is coupled to the torso 12 of user 10.

Phase oscillating system 20 includes an actuator 32 and a secondary mass or secondary body 34. Actuator 32 drives the oscillations of secondary body 34. Actuator 32 includes any suitable system that applies a force to secondary body 34 to cause oscillation or movement of secondary body 34. For example, actuator 32 is a linear actuator, pneumatic cylinder, hydraulic actuator, electromagnetic actuator, or another type of motor. Secondary body 34 is coupled to primary body 40 at any position, for example at torso 12 of user 10. Secondary body 34 may include any type of object, including a solid weight or combination of fluids of different densities. In one embodiment, secondary body 34 is an eccentric mass, and the eccentric mass is rotated to produce a desired external force. In another embodiment, secondary body 34 is a backpack, where the backpack is the oscillating mass in phase oscillating system 20.

Actuator 32 is coupled to secondary body 34 and acts on secondary body 34 to move secondary body 34 in a repetitive motion, such as a horizontal back and forth motion, a vertical up and down motion, a pendulum swing, rotary motion, or other linear or rotational motion. In one embodiment, secondary body 34 is accelerated up and down by actuator 32, and secondary body 34 oscillates up and down to create an external force, which acts on primary body 40. In another embodiment, the reaction force required to hold actuator 32 in place creates the external force on primary body 40.

A controller 36 is coupled to sensor 30 and actuator 32. Controller 36 receives and processes the physical state measurement from sensor 30. Based on the physical state measurement from sensor 30, controller 36 triggers actuator 32 to move secondary body 34. The movement of secondary body 34 produces an external force, which acts on primary body 40. Actuator 32 is engaged or triggered according to the physical state of primary body 40 in order to provide an external force that adds energy to or subtracts energy from the motion of primary body 40. In one embodiment, actuator 32 forces secondary body 34 to oscillate in phase with primary body 40 in order to add energy to the gait step of user 10. In an alternative embodiment, actuator 32 forces secondary body 34 to oscillate out of phase with primary body 40 in order to subtract energy from the gait step of user 10.

In an alternative embodiment, phase oscillating system 20 may include two or more actuators 32 and secondary bodies 34. A first actuator 32 is controlled to operate in phase with a first leg by oscillating a first secondary body 34 in phase with the first leg of user 10. A second actuator 32 is controlled to operate in phase with a second leg by oscillating a second secondary body 34 in phase with the second leg of user 10. The first actuator 32 triggers independently and in opposite phase of the second actuator 32. Similarly, the second actuator 32 triggers independently and in opposite phase of the first actuator 32. Phase oscillating system 20 with two or more actuators 32 and secondary bodies 34 adds energy to the gait of user 10 by oscillating one secondary body 34 in phase with each leg. Alternatively, each of the first and second actuators 32 and secondary bodies 34 may be controlled to oscillate out

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of phase with the corresponding leg of user **10** in order to hinder the gait cycle for user **10**. Therefore, two or more actuators **32** and secondary bodies **34** provide the phase oscillation to increase or decrease the power in the gait cycle of user **10**.

Phase oscillating system **20** provides the advantage of adding or subtracting energy when walking, jogging, running, carrying loads, climbing stairs, slopes, or hills, or reducing energy when walking down stairs or hills. Phase oscillating system **20** is also used to increase, maintain, or decrease vibrations in cars, airplanes, or appliances. Phase oscillating system **20** is also used as a mechanical amplifier to increase the energy harvested by energy harvesting devices. Phase oscillating system **20** is also used to alter the motion of a load being carried.

FIG. 1*c* shows a schematic representation of phase oscillating system **20**. The oscillation or movement of secondary body **34** produces external force U_1 by pulling on or pushing against primary body **40**. Secondary body **34** is oscillated based on the phase angle ϕ_1 of primary body **40**. By oscillating secondary body **34** in phase with respect to primary body **40**, energy is added to the motion of primary body **40**. By oscillating secondary body **34** out of phase with respect to primary body **40**, energy is subtracted from the motion of primary body **40**.

Sensor **30** is coupled to primary body **40** to measure a physical state of primary body **40**. A physical state of primary body **40** can be described by position Y_1, velocity $\dot{Y}_1$, acceleration $\ddot{Y}_1$, or a combination thereof. Sensor **30** detects the acceleration, velocity, or position of primary body **40**. Sensor **30** may comprise an accelerometer, vibrometer, rate gyro, or potentiometer. In one embodiment, sensor **30** is an accelerometer attached to primary body **40** to measure acceleration $\ddot{Y}_1$ of primary body **40**. The acceleration $\ddot{Y}_1$ is integrated once to determine velocity $\dot{Y}_1$ of primary body **40** and is integrated a second time to determine position Y_1 of primary body **40**. A phase angle ϕ_1 of primary body **40** is used to determine the external force U_1, which is applied by secondary body **34** to primary body **40**. A phase angle ϕ_1 of primary body **40** is determined by taking the arc tangent of velocity $\dot{Y}_1$ versus position Y_1 of primary body **40** and is represented by equation (1).

$$\phi_1 = a \tan 2(\dot{Y}_1, Y_1) \tag{1}$$

Where ϕ_1=phase angle of primary body **40**
$\dot{Y}_1$=velocity of primary body **40**
Y_1=position of primary body **40**
Alternatively, phase angle ϕ_1 of primary body **40** is determined by taking the arc tangent of acceleration $\ddot{Y}_1$ versus velocity $\dot{Y}_1$ of primary body **40** and is represented by equation (2).

$$\phi_1 = a \tan 2(\ddot{Y}_1, \dot{Y}_1) \tag{2}$$

Where ϕ_1=phase angle of primary body **40**
$\ddot{Y}_1$=acceleration of primary body **40**
$\dot{Y}_1$=velocity of primary body **40**
In one embodiment, phase angle ϕ_1 is a kinematic phase angle. A function of phase angle ϕ_1 is used to determine an external force U_1 to apply to primary body **40** and is represented generally by equation (3).

$$U_1 = f(\phi_1) \tag{3}$$

Where U_1=external force acting on primary body **40**
ϕ_1=phase angle of primary body **40**
In one embodiment, the sine of phase angle ϕ_1 is the function used to determine the external force U_1. The sine of phase angle ϕ_1 or other function of phase angle ϕ_1 can be used to

create a signal that varies between –1 and 1. The signal can be used to trigger actuator **32**. Phase oscillating system **20** provides external force U_1 based on the sine of phase angle ϕ_1 and is represented by equation (4).

$$m\ddot{Y}_1 + b\dot{Y}_1 + kY_1 = c\sin(\phi_1) = \frac{c\dot{Y}_1}{\sqrt{\dot{Y}_1^2 + Y_1^2}} \tag{4}$$

Where: m=mass of primary body **40**
$\ddot{Y}_1$=acceleration of primary body **40**
b=damping of primary body **40**
$\dot{Y}_1$=velocity of primary body **40**
k=spring constant of primary body **40**
c=constant
ϕ_1=phase angle of primary body **40**
Y=position of primary body **40**
A phase lock in amplifier or a phase locked loop is used to synchronize a sine generator from a signal from sensor **30**. A phase shift, delay, advance, change in amplitude, or change in sine is used to determine the desired external force U_1. By using the sine of phase angle ϕ_1 to determine external force U_1, the energy of phase oscillating system **20** remains bounded and stable.

In another embodiment, the magnitude of the oscillation of secondary body **34** is scaled by modifying equation (4) with a constant f as shown in equation (5).

$$m\ddot{Y}_1 + b\dot{Y}_1 + kY_1 = c\sin(\phi_1) = \frac{c\dot{Y}_1}{\sqrt{\dot{Y}_1^2 + fY_1^2}} \tag{5}$$

In another embodiment, the tangent of phase angle ϕ_1 is the function used to determine the external force U_1. Phase oscillating system **20** provides external force U_1 based on the tangent of phase angle ϕ_1 and is represented by equation (6). By using the tangent of phase angle ϕ_1 to determine external force U_1, the energy of phase oscillating system **20** remains bounded and stable.

$$m\ddot{Y}_1 + b\dot{Y}_1 + kY_1 = c\tan(\phi_1) = \frac{c\dot{Y}_1}{Y_1} \tag{6}$$

In another embodiment, the cosine of phase angle ϕ_1 is the function used to determine the external force U_1. Phase oscillating system **20** provides external force U_1 based on the cosine of phase angle ϕ_1 and is represented by equation (7).

$$m\ddot{Y}_1 + b\dot{Y}_1 + kY_1 = c\cos(\phi_1) = \frac{cY_1}{\sqrt{\dot{Y}_1^2 + Y_1^2}} \tag{7}$$

Cosine of phase angle ϕ_1 provides a damping system and reduces the energy of phase oscillating system **20**. The magnitude of oscillation of secondary body **34** is scaled by modifying equation (7) with a constant f as shown in equation (8).

$$m\ddot{Y}_1 + b\dot{Y}_1 + kY_1 = c\cos(\phi_1) = \frac{c\dot{Y}_1}{\sqrt{\dot{Y}_1^2 + f Y_1^2}} \qquad (8)$$

The desired external force U_1 is divided by a mass of secondary body **34** to determine an acceleration $\ddot{Y}_2$ desired for secondary body **34**. The desired acceleration $\ddot{Y}_2$ for secondary body **34** is integrated once to determine a velocity or velocity profile $\dot{Y}_2$ desired for secondary body **34**. Actuator **32** applies a force to secondary body **34** such that secondary body **34** moves in accordance with the desired velocity profile $\dot{Y}_2$. In another embodiment, the desired acceleration $\ddot{Y}_2$ of secondary body **34** is integrated twice to determine a position or position profile Y_2 desired for secondary body **34**, and actuator **32** applies a force to secondary body **34** such that secondary body **34** moves in accordance with the desired position profile Y_2.

External force U_1 is applied to primary body **40** by the oscillation or motion of secondary body **34** with respect to primary body **40**. Secondary body **34** oscillates such that secondary body **34** alternately applies positive and negative external forces U_1 on primary body **40**. By applying the positive and negative external forces U_1 at specific timing, the net effect enhances or increases movement of primary body **40**. Alternatively, external force U_1 decreases, resists, or limits motion of primary body **40** by applying external force U_1 in an opposing direction. In one embodiment, secondary body **34** moves in simple harmonic oscillation. In another embodiment, secondary body **34** moves linearly, circularly, elliptically, or in any other pattern. In an alternative embodiment, external force U_1 is applied to a body different than primary body **40**. For example, sensor **30** measures a physical state of primary body **40**, and phase oscillating system **20** applies external force U_1 to another portion of user **10**, such as lower limb **14** or upper limb **16**.

As secondary body **34** oscillates, the external force U_1 applied on primary body **40** by secondary body **34** alternates between a positive and negative force with respect to the direction of movement of primary body **40**. A negative velocity or force is referred to in FIG. **1c** to be in the same direction of gravity g, and a positive velocity or force is referred to as the opposite direction of gravity g in FIG. **1c**. Positive power results when external force U_1 is oriented in the same direction as the velocity $\dot{Y}_1$ of primary body **40**. Positive power enhances the motion of primary body **40**. Negative power results when external force U_1 is oriented in the opposite direction as the velocity $\dot{Y}_1$ of primary body **40**. Negative power inhibits and dampens the motion of primary body **40**.

When secondary body **34** applies a positive force on primary body **40** while primary body **40** is moving with a positive velocity, the positive force of secondary body **34** enhances the movement of primary body **40** by applying positive power. When secondary body **34** applies a negative force on primary body **40** while primary body **40** is moving with a negative velocity, the negative force enhances the movement of primary body **40** by applying positive power. By applying positive power at the correct times based on the phase angle ϕ_1 of primary body **40**, the net effect is to assist movement of primary body **40**.

When secondary body **34** applies a positive force on primary body **40** while primary body **40** is moving at a negative velocity, the positive force resists the movement on primary body **40** by applying negative power. When secondary body **34** applies a negative force on primary body **40** and while primary body **40** moves at a positive velocity, the negative

force resists the movement of primary body **40** by applying negative power. By applying negative power at the correct times based on the negative of the phase angle, the net effect is to resist movement of primary body **40**.

FIG. **1d** shows a phase portrait of phase oscillating system **20** for a gait step of user **10**. The leg of the human body can be described as a pendulum-like structure with inertia, damping, and a spring stiffness. To enhance the hopping motion of user **10** during gait, phase oscillating system **20** adds a parametric excitation force, external force U_1, to produce positive power for primary body **40**. The direction of external force U_1 is switched at a time and frequency that is tuned in phase with the frequency of the gait step. The phase portrait of a single gait step of user **10** is illustrated by line **50**.

Quadrant **52** represents the toe off phase of gait where user **10** has a positive velocity $\dot{Y}_1$ and is moving upwards in the air. To add positive power to the toe off phase for user **10**, phase oscillating system **20** provides a positive external force U_1. In order to provide a positive external force U_1 in quadrant **52**, secondary body **34** has a negative velocity $\dot{Y}_2$ and a negative acceleration $\ddot{Y}_2$.

Quadrant **58** represents the phase of gait where user **10** has a negative velocity $\dot{Y}_1$ and is falling back towards the ground. Phase oscillating system **20** provides a negative or downward external force U_1 to drive user **10** towards the ground. In order to add positive power in quadrant **58** to the falling phase for user **10**, phase oscillating system **20** provides a negative external force U_1. In order to provide a negative external force U_1 in quadrant **58**, secondary body **34** has a negative velocity $\dot{Y}_2$ and a positive acceleration $\ddot{Y}_2$.

Quadrant **56** represents user **10** landing where user **10** continues with a negative velocity $\dot{Y}_1$ toward the ground. Phase oscillating system **20** provides a negative or downward external force U_1 to further compress the legs, similar to compressing a spring. In order to add positive power in quadrant **56** phase oscillating system **20** provides a negative external force U_1. In order to provide a negative external force U_1 in quadrant **56**, secondary body **34** has a positive velocity $\dot{Y}_2$ and a positive acceleration $\ddot{Y}_2$.

Quadrant **54** represents user **10** extending the legs and pushing off the ground. In order to add positive power in quadrant **54** to the push off phase of gait for user **10**, phase oscillating system **20** provides a positive external force U_1. In order to provide a positive external force U_1 in quadrant **54**, secondary body **34** has a positive velocity $\dot{Y}_2$ and a negative acceleration $\ddot{Y}_2$.

To hinder or dampen the hopping motion of user **10** during gait, phase oscillating system **20** provides a negative power. The direction of external force U_1 is switched at a time and frequency that is tuned in anti-phase with the frequency of the gait step. To subtract or absorb energy to the toe off phase for user **10**, phase oscillating system **20** provides a positive external force U_1 in quadrants **56** and **54** and provides a negative external force U_1 in quadrants **52** and **58**.

FIG. **1e** shows a schematic representation of the motion of an alternative phase oscillating system **60** including a suspension system. Phase oscillating system **60** is similar to phase oscillating system **20** and includes suspension system **62**. A suspension system **62** is coupled to primary body **40** at a first end **64** and is coupled to secondary body **34** at a second end **66**. Suspension system **62** permits second end **66** to move in relative motion to first end **64**. Suspension system **62** includes a plurality of spring forces and damper forces. Suspension system **62** may include springs, air springs, air pistons, dampers, and bumpers. In one embodiment, suspension system **62** includes spring **68**, where spring **68** is a compliant element such as a helical or coil spring. Secondary body **34** is coupled

to primary body 40 by actuator 32 and spring 68 or a similar mechanism that allows secondary body 34 to oscillate passively with respect to primary body 40. Oscillating secondary body 34 enhances or maintains a limit cycle based on moving secondary body 34 as a function of phase angle ϕ_1. Alternatively, oscillating secondary body 34 decreases the limit cycle based on moving secondary body 34 as a function of phase angle ϕ_1.

Suspension system 62 assists secondary body 34 in increasing the vertical up and down motion of primary body 40 relative to the ground. Secondary body 34 coupled to second end 66 of suspension system 62 moves relative to the ground and relative to first end 64 in phase with primary body 40. Suspension system 62 thereby increases the up and down motion of primary body 40 relative to the ground. Secondary body 34 coupled to second end 66 moves up relative to first end 64 when first end 64 moves downward relative to the ground, and moves down relative to said first end 64 when first end 64 moves upward relative to the ground. Suspension system 62 thereby increases the up and down motion of primary body 40 relative to the ground. Secondary body 34 coupled to second end 66 moves up and accelerates up when primary body 40 touches the ground, moves up and accelerates down when primary body 40 pushes off the ground, moves down and accelerates down when primary body 40 moves up in the air, and moves down and accelerate up when primary body 40 falls in the air. In another embodiment, the motion of primary body 40 and secondary body 34 is nonvertical and can be in any direction. Suspension system 62 thereby enhances, increases, or assists the motion of primary body 40.

In an alternative embodiment, suspension system 62 assists secondary body 34 in decreasing or reducing the vertical up and down motion of primary body 40 relative to the ground. Secondary body 34 coupled to second end 66 moves relative to the ground and relative to first end 64 out of phase with primary body 40 and thereby decreases the up and down motion of primary body 40 relative to the ground. Secondary body 34 coupled to second end 66 moves down relative to first end 64 when first end 64 moves downward relative to the ground, and moves up relative to first end 64 when first end 64 moves upward relative to the ground, thereby decreasing or reducing the up and down motion of primary body 40 relative to the ground. Secondary body 34 coupled to second end 66 moves down and accelerates down when primary body 40 coupled to first end 64 touches the ground, moves down and accelerates up when primary body 40 pushes off the ground, moves up and accelerates up when primary body 40 moves up in the air, and moves up and accelerates down when primary body 40 falls in the air, thereby reducing or decreasing the motion of primary body 40. In another embodiment, the motion of primary body 40 and secondary body 34 is nonvertical and can be in any direction.

Phase oscillating system 20 enhances human motion and reduces the metabolic cost of motion. Phase oscillating systems 20 and 60 assist at different speeds of motion, because a continuous control signal is generated and used as a triggering mechanism. For example, phase oscillating systems 20 and 60 smoothly transition from walking to running and back to walking. Phase oscillating systems 20 and 60 provide a bounded energy and works for linear and rotary systems. Alternatively, phase oscillating system 20 provides a damping of energy to hinder motion, which is useful in exercise or training applications and during downhill walking and running.

FIG. 1f shows a schematic representation of the motion of an alternative phase oscillating system 70 that harvests

energy from a damper. Phase oscillating system 70 optionally includes a spring 72 and a damper 74 coupled to primary body 40. One or more dampers 74 may be coupled to primary body 40. Dampers 74 harvest energy from the motion of primary body 40. Dampers 74 harvest energy expended by phase oscillating system 70. The harvested energy is stored for use by phase oscillating system 70 or by another device at a future time. In one embodiment, secondary body 34 is oscillated at a rate to increase the amount of energy harvested from damper 74.

FIGS. 2a-2c show another phase oscillating system, which oscillates in any direction or angle with respect to the ground. FIG. 2a shows phase oscillating system 80. Phase oscillating system 80 is similar to phase oscillating system 20 in that phase oscillating system 80 is a device that oscillates a secondary body or secondary mass 82, which applies an external force to primary body 40. Additionally, phase oscillating system 80 can be positioned at any angle with respect to user 10 and the direction of motion of user 10.

Phase oscillating system 80 is coupled to primary body 40. User 10 is the primary body 40 in phase oscillating system 80. The external forces created by phase oscillating system 80 act on primary body 40, user 10. The force applied to user 10 by phase oscillating system 80 increases or decreases the power of the user's motion. User 10 wears phase oscillating system 80, or phase oscillating system 80 is coupled to the user by an attachment system. In one embodiment, the attachment system includes a frame 86 and straps 88, which are secured to torso 12 of user 10. In another embodiment, the attachment system includes straps, which secure phase oscillating system 80 to an upper limb 16 or a lower limb 14 of user 10. In yet another embodiment, phase oscillating system 80 is coupled to an exoskeleton, which is coupled to user 10 or worn by user 10.

FIG. 2b shows phase oscillating system 80. In one embodiment, phase oscillating system 80 is a belt system and includes secondary body 82, belt 90, actuator 92, and tensioner 94. Belt 90 may include a chain, rope, or any other device capable of rotating about a tensioner 94. Actuator 92 drives belt 90. Secondary body 82 is coupled to belt 90 and actuator 92 such that secondary body 82 moves in conjunction with belt 90. Belt 90 may move secondary body 82 in a circular, elliptical, pendulum, vertical up and down, horizontal side to side, or other motion in any direction. Alternatively, phase oscillating system 80 includes any suitable system that applies a force to secondary body 82 to cause oscillation or movement of secondary body 82. For example, actuator 92 is a linear actuator, pneumatic cylinder, hydraulic actuator, electromagnetic actuator, or another type of motor. Secondary body 82 may include any type of object, including a solid weight or combination of fluids of different densities. In one embodiment, secondary body 84 is an eccentric mass, and the eccentric mass is rotated to produce a desired external force. In another embodiment, secondary body 82 is a backpack, where the backpack is the oscillating mass in phase oscillating system 80.

Phase oscillating system 80 includes axle 96, which allows phase oscillating system 80 to be rotated about axle 96 and positioned at any angle with respect to user 10. Secondary body 82, belt 90, actuator 92, and tensioner 94 are mounted at a selected angle on axle 96. Phase oscillating system 80 is mounted to user 10 to increase or decrease the energy of the user's motion.

FIG. 2c shows a schematic representation of phase oscillating system 80. Phase oscillating system 80 is coupled to primary body 40 to assist or resist movement of primary body 40. Phase oscillating system 80 operates similarly to phase

oscillating system **20**, except that the axis along which secondary body **82** moves, the direction of motion of secondary body **82**, is adjustable. Phase oscillating system **80** may be positioned at any suitable angle relative to primary body **40** to assist or resist movement of primary body **40**.

Phase oscillating system **80** further includes secondary body **82**, actuator **92**, controller **100**, and sensor **102**. Sensor **102** is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, or other sensor. Sensor **102** measures a physical state of primary body **40**. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement. Primary body **40** can be a portion of user **10**, such as the torso **12**, lower limbs **14**, and upper limbs **16**, or other body portion of user **10**. In one embodiment, sensor **102** is coupled to the torso **12** of user **10**.

Controller **100** is coupled to sensor **102** and actuator **92**. Controller **100** receives and processes a physical state measurement from sensor **102**. Based on the physical state measurement from sensor **102**, controller **100** triggers actuator **92** to move secondary body **82**. The movement of secondary body **82** produces an external force, which acts on primary body **40**. Actuator **92** is engaged or triggered according to the physical state of primary body **40** in order to provide an external force that adds energy to or subtracts energy from the motion of primary body **40**. In one embodiment, actuator **92** forces secondary body **82** to oscillate in phase with primary body **40** in order to add energy to the gait step of user **10**. In an alternative embodiment, actuator **92** forces secondary body **82** to oscillate out of phase with primary body **40** in order to subtract energy from the gait step of user **10**.

Phase oscillating system **80** enhances human motion and reduces the metabolic cost of motion. Phase oscillating system **80** assists different speeds of motion, because a continuous control signal is generated and used as a triggering mechanism. For example, phase oscillating system **80** smoothly transitions from walking to running and back to walking. Phase oscillating system **80** provides a bounded energy and works for linear and rotary systems. Alternatively, phase oscillating system **80** provides a damping of energy to hinder motion, which is useful in exercise or training applications and during downhill walking and running.

FIGS. **3a**-**3c** show a schematic representation of a phase oscillating system worn on the limb of the user. FIG. **3a** shows phase oscillating system **110**, which is similar to phase oscillating system **20** or **80** and is coupled to primary body **112**. Primary body **112** may include any suitable body. Phase oscillating system **110** is coupled to user **10** or is worn on any portion of user **10**. In one embodiment, primary body **112** is lower limb **14** of user **10**. Alternatively, phase oscillating system **110** is coupled to any primary body, which can be a human, animal, robot, or other object.

Phase oscillating system **110** includes sensor **120**, actuator **122**, secondary body **124**, and controller **126**. Sensor **120** is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, or other sensor. Sensor **120** measures a physical state of primary body **112**. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement. In an alternative embodiment, sensor **120** measure the physical state of another portion of user **10** different than primary body **112**. Actuator **122** drives the oscillations of secondary body **112**. Actuator **122** includes any suitable system that applies a force to secondary body **124** to cause oscillation or movement of second-

ary body **124**. For example, actuator **122** is a linear actuator, pneumatic cylinder, hydraulic actuator, electromagnetic actuator, or another type of motor. Secondary body **124** may include any type of object, including a solid weight or combination of fluids of different densities. In one embodiment, secondary body **124** is an eccentric mass, and the eccentric mass is rotated to produce a desired external force.

Controller **126** includes a microprocessor coupled to sensor **120** and actuator **122**. Controller **126** receives and processes a physical state measurement signal from sensor **120**. Based on the physical state measurement from sensor **120**, controller **126** triggers actuator **122** to move secondary body **124**. The movement of secondary body **124** produces an external force, which acts on primary body **112**. In one embodiment, actuator **122** forces secondary body **124** to oscillate in phase with primary body **112** in order to add energy to the gait step of user **10**. In an alternative embodiment, actuator **122** forces secondary body **124** to oscillate out of phase with primary body **112** in order to subtract energy from the gait step of user **10**.

FIG. **3b** shows a schematic diagram of the operation of phase oscillating system **110**. Primary body **112** moves or rotates with respect to pivot point **130**. Pivot point **130** represents a pivot point for primary body **112**, such as the hip joint of user **10**. Secondary body **124** is disposed within a link **132** that couples primary body **112** to pivot point **130**. Secondary body **124** oscillates linearly with respect to primary body **112** and pivot point **130**, while primary body **112** and link **132** rotate with respect to pivot point **130**. The oscillation or movement of secondary body **124** produces external force U_1, which acts on primary body **112**.

Secondary body **124** driven by actuator **122** using electric energy, pneumatic energy, or any other type of energy. Phase oscillating system **110** includes an optional suspension system **140** coupled to secondary body **124**. Suspension system **140** permits secondary body **124** to move in relative motion to pivot point **130** and primary body **112**. Suspension system **140** includes a plurality of spring forces and damper forces. Suspension system **140** may include springs, air springs, air pistons, dampers, and bumpers. In one embodiment, suspension system **140** includes a compliant element such as a helical or coil spring.

Sensor **120** is coupled to primary body **112** to measure a physical state of primary body **112**. A physical state of primary body **112** can be described by angular position θ, angular velocity $\dot{\theta}$, angular acceleration $\ddot{\theta}$, or a combination thereof. Sensor **120** may detect the angular velocity $\dot{\theta}$ of primary body **112** at lower limb **14** of user **10**. Alternatively, sensor **120** may further detect the angular acceleration $\ddot{\theta}$ of primary body **112** at lower limb **14** of user **10**. In one embodiment, sensor **120** is an accelerometer coupled to primary body **112** to measure angular acceleration $\ddot{\theta}$ of primary body **112**. The angular velocity $\dot{\theta}$ is determined by taking the integral of angular acceleration $\ddot{\theta}$ of primary body **112**, and angular position θ is determined by taking the integral of angular velocity $\dot{\theta}$. Angular position θ of primary body **112** may be defined as the angle that primary body **112** makes relative to a plane **134**. In one embodiment, plane **134** is horizontal to the ground.

A phase angle ϕ of primary body **112** is used to determine the external force U_1, which is applied by secondary body **124** to primary body **112**. Secondary body **124** is oscillated based on the phase angle ϕ of primary body **112**. By oscillating secondary body **124** in phase with respect to primary body **112**, energy is added to the motion of primary body **112**. By oscillating secondary body **124** out of phase with respect to primary body **112**, energy is subtracted from the motion of

primary body 112. A phase angle ϕ of primary body 112 is determined by taking the arc tangent of angular velocity $\dot{\theta}$ versus angular position θ of primary body 112 and is represented by equation (9).

$$\phi = a\tan 2(\dot{\theta}, \theta) \tag{9}$$

Where ϕ=phase angle of primary body 112
$\dot{\theta}$=angular velocity of primary body 112
θ=angular position of primary body 112

Alternatively, phase angle ϕ of primary body 112 is determined by taking the arc tangent of angular acceleration $\ddot{\theta}$ versus angular velocity $\dot{\theta}$ of primary body 112 and is represented by equation (10).

$$\phi = a\tan 2(\ddot{\theta}, \dot{\theta}) \tag{10}$$

Where ϕ=phase angle of primary body 112
$\ddot{\theta}$=angular acceleration of primary body 112
$\dot{\theta}$=angular velocity of primary body 112

In one embodiment, phase angle ϕ is a kinematic phase angle. A function of phase angle ϕ is used to determine an external force U_1 to apply to primary body 112 and is represented generally by equation (11).

$$U_1 = f(\phi) \tag{11}$$

Where U_1=external force acting on primary body 112
ϕ=phase angle of primary body 112

In one embodiment, the sine of phase angle ϕ_1 is the function used to determine the external force U_1. The function of phase angle ϕ_1 can be used to create a signal that varies between –1 and 1. The signal can be used to trigger actuator 122. Phase oscillating system 110 provides external force U_1 based on the sine of phase angle ϕ and is represented by equation (12).

$$I\ddot{\theta} + b\dot{\theta} + k\theta = c\sin(\phi) = \frac{c\dot{\theta}}{\sqrt{\dot{\theta}^2 + \theta^2}} \tag{12}$$

Where: I=inertia of primary body 112
$\ddot{\theta}$=angular acceleration of primary body 112
b=damping of primary body 112
$\dot{\theta}$=angular velocity of primary body 112
k=spring constant of primary body 112
c=constant
ϕ=phase angle of primary body 112
θ=angular position of primary body 112

A phase lock in amplifier or a phase locked loop is used to synchronize a sine generator from a signal from sensor 120. A phase shift, delay, advance, change in amplitude, or change in sine is used to determine the desired external force U_1. By using the sine of phase angle ϕ to determine external force U_1, the energy of phase oscillating system 110 remains bounded and stable.

In another embodiment, the magnitude of the oscillation of secondary body 124 is scaled by modifying equation (12) with a constant f, similarly to equation (5). In another embodiment, the tangent of phase angle ϕ is the function used to determine the external force U_1. By using the tangent of phase angle ϕ to determine external force U_1, the energy of phase oscillating system 110 remains bounded and stable. In yet another embodiment, the cosine of phase angle ϕ is the function used to determine the external force U_1. Cosine of phase angle ϕ provides a damping system and reduces the energy of phase oscillating system 110. The magnitude of oscillation of secondary body 124 is scaled by modifying equation (12) with a constant f, similarly to equation (8).

External force U_1 is applied to primary body 112 by the oscillation or motion of secondary body 124 with respect to primary body 112. Secondary body 124 oscillates such that secondary body 124 alternately applies positive and negative external forces U_1 on primary body 112. By applying the positive and negative external forces U_1 at specific timing, the net effect enhances or increases movement of primary body 112. Alternatively, external force U_1 decreases, resists, or limits motion of primary body 112 depending on the direction of external force U_1 applied to primary body 112. In one embodiment, secondary body 124 moves in simple harmonic oscillation. In another embodiment, secondary body 124 moves linearly, circularly, elliptically, or in any other pattern.

The leg of the human body can be described as a pendulum-like structure with inertia, damping, and a spring stiffness. To enhance add power to user 10 during gait, phase oscillating system 110 enhances the pendulum motion of lower limb 14. The direction of external force U_1 is switched at a time and frequency that is tuned in phase with the frequency of the gait step. A plurality of phase oscillating systems 110 can be attached to user 10. For example, one phase oscillating system 110 is attached to each lower limb 14, and each phase oscillating system 110 is tuned in phase with one lower limb 14. Phase oscillating system 110 may also include a damper placed at the hip, pivot point 130, to harvest energy.

Phase oscillating system 110 enhances human motion and reduces the metabolic cost of motion. Phase oscillating system 110 assists different speeds of motion, because a continuous control signal is generated and used as a triggering mechanism. For example, phase oscillating system 110 smoothly transitions from walking to running and back to walking. Phase oscillating system 110 provides a bounded energy and works for linear and rotary systems. Alternatively, phase oscillating system 110 provides a damping of energy to hinder motion, which is useful in exercise or training applications and during downhill walking and running.

FIG. 3c shows an alternative phase oscillating system 150. Phase oscillating system 150 is similar to phase oscillating system 110, except that phase oscillating system 150 includes a swinging or rotating a secondary mass or secondary body 152. Secondary body 152 is coupled to primary body 112 at any suitable point on primary body 112. In one embodiment, secondary body 152 is coupled to primary body 112 at point 154. An actuator 156 applies a torque to secondary body 152.

The appropriate torque may be determined based on a function of the phase angle and the mass of secondary body 152. By applying torque at the appropriate time, secondary body 152 assists locomotion of primary body 112. In one embodiment, the torque from actuator 156 causes secondary body 152 to swing in a pendulum motion. In another embodiment, the torque from actuator 156 causes secondary body 152 to complete full revolutions about point 154. In one embodiment, the period of the swing of secondary body 152 may be substantially similar to a frequency of motion of primary body 112. In another embodiment, the period may be offset in order to maximize the locomotive effect. In yet another embodiment, the period of secondary body 152 may be shorter or longer than the period of primary body 112.

Phase oscillating system 150 includes an optional suspension system 158 coupled to secondary body 124. Suspension system 158 may include a plurality of spring forces and damper forces. Suspension system 158 may include springs, air springs, air pistons, dampers, and bumpers. In one embodiment, suspension system 158 includes a compliant element such as a helical or coil spring. Suspension system 158 is coupled to link 132 and to secondary body 152. In one embodiment, secondary body 152 is an offset eccentric mass

and suspension system **158** permits secondary body **152** to move in relative motion to link **132**.

Phase oscillating system **150** may be mounted on torso **12** of user **10** or may be coupled to other portions of the user's body. Phase oscillating system **150** applies a torque to alter body motion by adding or subtracting energy based on the motion of primary body **112**, user **10**. Phase oscillating system **150** adds or subtracts rotational kinetic energy to primary body **112**.

FIGS. **4***a*-**4***e* show a phase oscillating system worn on the hip of the user. FIG. **4***a* shows phase oscillating system **170** worn by user **10**. Phase oscillating system **170** applies a direct oscillating torque to a joint of user **10**. The leg of the human body can be described as a pendulum-like structure with inertia, damping, and a spring stiffness. To enhance the pendulum motion of user's lower limbs **14**, a parametric excitation torque is added by phase oscillating system **170**. User **10** wears phase oscillating system **170** on upper leg or thigh **172**. The direction of the torque provided by phase oscillating system **170** is switched at the correct timing and frequency to be tuned with the gait frequency of user **10**.

Phase oscillating system **170** is coupled to the user by an attachment system **174**. In one embodiment, attachment system **174** includes straps, which are secured to thigh **172** of user **10**. In another embodiment, attachment system **174** includes straps, which secure phase oscillating system **170** to another portion of user **10**, such as upper limb **16**. In yet another embodiment, phase oscillating system **170** is coupled to an exoskeleton or frame, which is coupled to user **10** or worn by user **10**.

FIG. **4***b* shows a schematic representation of phase oscillating system **170** worn on thigh **172** of user **10**. Phase oscillating system **170** is attached to primary body **180**, which is lower limb **14**. Phase oscillating system **170** includes a sensor **182**, an actuator **184**, and a controller **186**. Phase oscillating system **170** operates by oscillating the force of actuator **184** back and forth with respect to primary body **180**. Actuator **184** produces a direct torque at hip joint **190** by pulling on or pushing against primary body **180**. The external forces produced by phase oscillating system **170** act on user **10** at the hip joint **190** to rotate lower limb **14** about hip joint **190**.

Phase oscillating system **170** includes a sensor **182** coupled to user **10**. Sensor **182** is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, or other sensor. Sensor **182** measures a physical state of a primary body **180**. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement. A controller **186** is coupled to sensor **182** and actuator **184**. Controller **186** receives and processes the physical state measurement from sensor **182**. Based on the physical state measurement from sensor **182**, controller **186** triggers actuator **184**. Actuator **184** includes any suitable system that applies a force or torque to primary body **180** that assists or restricts movement of primary body **180**. For example, actuator **184** is a linear actuator, pneumatic cylinder, hydraulic actuator, electromagnetic actuator, air ratchet, fly wheel with motor, or another type of linear or rotary motor.

FIG. **4***c* shows phase oscillating system **170** worn by user **10**. Phase oscillating system **170** is incorporated into exoskeleton **194**, which is coupled to user **10** or worn by user **10**. A torque τ is applied by actuator **184** at hip joint **190**. In one embodiment, a force is applied by actuator **184** to lower limb **14** or thigh **172** to produce a torque at hip joint **190**. Alternatively, torque at hip joint **190** is applied directly to user **10** at hip joint **190**.

FIG. **4***d* shows an isometric view of phase oscillating system **170** worn by user **10** with exoskeleton **194**. Torque τ is applied by actuator **184** to primary body **180** at hip joint **190**. In one embodiment, actuator applies **184** torque τ in phase with primary body **180** in order to add energy to the gait step of user **10**. In an alternative embodiment, actuator applies **184** torque τ out of phase with primary body **180** in order to subtract energy from the gait step of user **10**.

A plurality of phase oscillating systems **170** can be attached to exoskeleton **194** or user **10**. For example, one phase oscillating system **170** is attached to each lower limb **14**, and each phase oscillating system **170** is tuned in phase with one lower limb **14**. Phase oscillating system **170** may also include a damper placed at the hip, pivot point **130**, to harvest energy.

FIG. **4***e* shows a schematic representation of phase oscillating system **170**. The leg of the human body can be described as a pendulum-like structure with inertia, damping, and a spring stiffness. To enhance the motion of user **10** during gait, phase oscillating system **170** adds a parametric excitation force, torque τ, to produce positive power for primary body **180**. The direction of torque τ is switched at a time and frequency that is tuned in phase with the frequency of the gait step.

Torque τ is applied by actuator **184** to primary body **180** according to the phase angle φ of primary body **180**. The phase angle φ of primary body **180** is calculated based on the physical state of primary body **180** as measured by sensor **182**. Sensor **182** is coupled to primary body **180** to measure a physical state of primary body **180**. Alternatively, sensor **182** is coupled to another portion of user **10** different than primary body **180**. A physical state of primary body **180** can be described by angular position θ, angular velocity $\dot{\theta}$, angular acceleration $\ddot{\theta}$, or a combination thereof. Sensor **182** may detect the angular velocity $\dot{\theta}$ of primary body **180** at lower limb **14** of user **10**. Alternatively, sensor **182** may further detect the angular acceleration $\ddot{\theta}$ of primary body **180** at lower limb **14** of user **10**. In one embodiment, sensor **182** is an accelerometer coupled to primary body **180** to measure angular acceleration $\ddot{\theta}$ of primary body **180**. The angular velocity $\dot{\theta}$ is determined by taking the integral of angular acceleration $\ddot{\theta}$ of primary body **180**, and angular position θ is determined by taking the integral of angular velocity $\dot{\theta}$. Angular position θ of primary body **180** may be defined as the angle that primary body **180** makes relative to a plane **198**. In one embodiment, plane **198** is horizontal to the ground.

A phase angle φ of primary body **180** is used to determine the torque τ, which is applied by actuator **184** to primary body **180**. A phase angle φ of primary body **180** is determined by taking the arc tangent of angular velocity $\dot{\theta}$ versus angular position θ or angular acceleration $\ddot{\theta}$ versus angular velocity $\dot{\theta}$ of primary body **180**. In one embodiment, phase angle φ is a kinematic phase angle.

A function of phase angle φ is used to determine the torque τ to apply to primary body **180**. In one embodiment, the sine of phase angle φ is the function used to determine the torque τ to be applied to primary body **180**. The sine of phase angle φ or other function of phase angle φ can be used to create a signal that varies between −1 and 1. The signal can be used to trigger actuator **184**. A phase lock in amplifier or a phase locked loop is used to synchronize a sine generator from a signal from sensor **182**. A phase shift, delay, advance, change in amplitude, or change in sine is used to determine the desired torque τ. By using the sine of phase angle φ to determine torque τ, the energy of phase oscillating system **170** remains bounded and stable. In another embodiment, the tangent of phase angle φ is the function used to determine the

external force U_1. By using the tangent of phase angle φ to determine external force U_1, the energy of phase oscillating system 170 remains bounded and stable. In yet another embodiment, the cosine of phase angle φ is the function used to determine the external force U_1. Cosine of phase angle φ provides a damping system and reduces the energy of phase oscillating system 170. Other functions, including arctangent, arcsine, arccosine, or another function of phase angle φ can be used to determine torque τ. Additionally, the functions can be scaled using a constant in order to scale the magnitude of torque τ.

By applying the positive and negative torque τ at hip joint 190 at specific timing, the net effect enhances or increases movement of primary body 180. Alternatively, torque τ in an opposing direction to decrease, resist, or limit motion of primary body 180. In one embodiment, actuator 184 applies torque τ in simple harmonic oscillation.

Phase oscillating system 170 enhances human motion and reduces the metabolic cost of motion. Phase oscillating system 170 assists different speeds of motion, because a continuous control signal is generated and used as a triggering mechanism. For example, phase oscillating system 170 smoothly transitions from walking to running and back to walking. Phase oscillating system 170 provides a bounded energy and works for linear and rotary systems. Alternatively, phase oscillating system 170 provides a damping of energy to hinder motion, which is useful in exercise or training applications and during downhill walking and running.

FIGS. 5a-5d show a biarticular phase oscillating system. FIG. 5a shows phase oscillating system 200 worn on a lower limb 14 of user 10. Phase oscillating system 200 applies a direct force to a limb of user 10. User 10 wears phase oscillating system 200 coupled to thigh 172 and foot 202. Phase oscillating system 200 is biarticular, meaning the phase oscillating system 200 extends across two joints. In one embodiment, phase oscillating system 200 extends between thigh 172 and foot 202 across the knee joint and the ankle joint.

Phase oscillating system 200 is coupled to the user by an attachment system 204. In one embodiment, attachment system 204 includes straps, which are secured to torso 12, thigh 172, and foot 202 of user 10. In another embodiment, attachment system 204 includes straps, which secure phase oscillating system 200 to another portion of user 10, such as upper limb 16. In yet another embodiment, phase oscillating system 200 is coupled to an exoskeleton or frame, which is coupled to user 10 or worn by user 10.

FIG. 5b shows a schematic representation of phase oscillating system 200 extending between thigh 172 and foot 202 across the knee joint and the ankle joint. Phase oscillating system 200 is attached to primary body 210, which is lower limb 14. Phase oscillating system 200 includes a sensor 212, an actuator 214, a controller 216, and a compliant element 218. Actuator 214 produces a linear force that pulls on foot 202. The external forces produced by phase oscillating system 200 act on user 10 at foot 202 across the knee joint 220 and the ankle joint 222.

Sensor 212 is coupled to user 10 at any point on primary body 210 or lower limb 14. Sensor 212 is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, or other sensor. Sensor 212 measures a physical state of a primary body 210. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement. Controller 216 is coupled to sensor 212 and actuator 214. Controller 216 receives and processes the physical state measurement from sensor 212. Based on the physical state measurement from sensor 212,

controller 216 triggers actuator 214. Actuator 214 includes any suitable system that applies a force to foot 202 to assist movement of primary body 210. For example, actuator 214 is a linear actuator, pneumatic cylinder, hydraulic actuator, electromagnetic actuator, or another type of motor.

FIG. 5c shows phase oscillating system 200 worn by user 10. Phase oscillating system 200 is incorporated into exoskeleton 230, which is coupled to user 10 or worn by user 10. A force F is applied by actuator 214 to pull on foot 202 during a push off phase of gait. Actuator 214 applies force F in phase with primary body 210 in order to add energy to the gait step of user 10. Force F is applied to foot 202 based on a phase angle φ of primary body 210. The phase angle φ of primary body 210 is calculated based on the physical state of primary body 210 as measured by sensor 212. In one embodiment, a sine of phase angle φ is used to determine force F. A phase lock in amplifier or a phase locked loop is used to synchronize a sine generator from a signal from sensor 212. A phase shift, delay, advance, change in amplitude, or change in sine is used to determine the desired force F. By using the sine of phase angle φ to determine force F, the energy of phase oscillating system 200 remains bounded and stable.

FIG. 5d shows phase oscillating system 200 worn by user 10 during the push off phase of gait. A positive force F is applied to the heel of foot 202 to assist user 10 in plantar flexing at ankle joint 222 to lift the heel and push off the ground. By applying the positive force F at foot 202 at specific timing, the net effect enhances or increases movement of primary body 210. A plurality of phase oscillating systems 200 can be attached to exoskeleton 230 or user 10. For example, one phase oscillating system 200 is attached to each lower limb 14, and each phase oscillating system 200 is tuned in phase with one lower limb 14.

Phase oscillating system 200 enhances human motion and reduces the metabolic cost of motion. Phase oscillating system 200 assists different speeds of motion, because a continuous control signal is generated and used as a triggering mechanism. For example, phase oscillating system 200 smoothly transitions from walking to running and back to walking. Phase oscillating system 200 provides a bounded energy and works for linear and rotary systems.

FIGS. 6a-6c show a combination phase oscillating system. FIG. 6a shows phase oscillating system 170 worn by user 10 on the hip and phase oscillating system 200 extending between thigh 172 and foot 202 of user 10. Phase oscillating system 240 incorporates phase oscillating systems 170 and 200 into one device. Phase oscillating system 240 is coupled to the user by an attachment system 242. In one embodiment, attachment system 242 includes straps, which are secured to torso 12, thigh 172, and foot 202 of user 10. In another embodiment, attachment system 242 includes straps, which secure phase oscillating system 240 to another portion of user 10, such as upper limb 16. In yet another embodiment, phase oscillating system 200 is coupled to an exoskeleton or frame, which is coupled to user 10 or worn by user 10.

FIG. 6b shows a schematic representation of phase oscillating system 240. Phase oscillating system 240 includes a sensor 244 and a controller 246. Sensor 244 is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, or other sensor. Sensor 244 measures a physical state of a primary body 250. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement. Controller 246 receives and processes the physical state measurement from sensor 244. Based on the physical state measurement from sensor 244, controller 246 triggers actuators 184 and 214.

Actuators **184** and **214** may be linear actuators, pneumatic cylinders, hydraulic actuators, electromagnetic actuators, or another type of motor.

FIG. **6c** shows the forces applied to user **10** by phase oscillating system **240**. Torque τ is applied by actuator **184** to primary body **250** at hip joint **190**. In one embodiment, actuator **184** applies torque τ in phase with primary body **250** in order to add energy to the gait step of user **10**. Actuator **214** produces a linear force that pulls on foot **202**. The force F is applied by actuator **214** to pull on foot **202** during a push off phase of gait. Actuator **214** applies force F in phase with primary body **250** in order to add energy to the gait step of user **10**. Force F and torque τ are applied to user **10** based on a phase angle ϕ of primary body **250**. The phase angle ϕ of primary body **250** is calculated based on the physical state of primary body **250** as measured by sensor **244**. In one embodiment, a sine of phase angle ϕ is used to determine force F and torque τ. A phase lock in amplifier or a phase locked loop is used to synchronize a sine generator from a signal from sensor **244**. A phase shift, delay, advance, change in amplitude, or change in sine is used to determine the desired force F. By using the sine of phase angle ϕ to determine force F and torque τ, the energy of phase oscillating system **240** remains bounded and stable.

Phase oscillating system **240** enhances human motion and reduces the metabolic cost of motion. Phase oscillating system **240** assists different speeds of motion, because a continuous control signal is generated and used as a triggering mechanism. For example, phase oscillating system **240** smoothly transitions from walking to running and back to walking. Phase oscillating system **240** provides a bounded energy and works for linear and rotary systems. Alternatively, phase oscillating system **240** provides a damping of energy to hinder motion, which is useful in exercise or training applications and during downhill walking and running.

FIGS. **7a-7b** show a phase oscillating system including a ducted fan. Phase oscillating system **280** applies an external force to user **10** using one or more ducted fans **282**. User **10** wears a phase oscillating system **280** in order to increase or decrease the available power during movement of user **10**, for example, during gait or other activities. Phase oscillating system **280** senses motion of the human body and responds by adding a negative or a positive external force. The external forces created by the ducted fan increases the horizontal ground reaction force to add energy to the gait of user **10**.

User **10** wears phase oscillating system **280**, or phase oscillating system **280** is coupled to the user by an attachment system **284**. In one embodiment, attachment system **284** includes straps, which are secured to a torso of user **10**. In another embodiment, attachment system **284** includes straps, which secure phase oscillating system **280** to an upper limb **16** or a lower limb **14** of user **10**. In yet another embodiment, phase oscillating system **280** is coupled to an exoskeleton or frame, which is coupled to user **10** or worn by user **10**.

Phase oscillating system **280** includes a sensor **290**, one or more actuators **292**, and one or more ducted fans **282**. Phase oscillating system **280** is attached to a primary body **294**. Primary body **40** may be torso **12**, lower limbs **14**, and upper limbs **16**, or other body portion of user **10**. Primary body **294** is a human, animal, robot, or other object. In one embodiment, torso **12** of user **10** represents primary body **294**. Sensor **290** is coupled to user **10**. Sensor **290** is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, or other sensor. Sensor **290** measures a physical state of a primary body **294**. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement.

A controller **296** is coupled to sensor **290** and actuator **292**. Controller **296** receives and processes the physical state measurement from sensor **290**. Based on the physical state measurement from sensor **290**, controller **296** triggers actuator **292** to direct the airflow of ducted fans **282**. The airflow of ducted fans **282** produces an external force, which acts on primary body **294**. Actuator **292** is engaged or triggered according to the physical state of primary body **294** in order to provide an external force that adds energy to or subtracts energy from the motion of primary body **294**.

In one embodiment, sensor **290** is an accelerometer attached to primary body **294** to measure acceleration $\ddot{Y}_1$ of primary body **294**. The acceleration $\ddot{Y}_1$ is integrated once to determine velocity $\dot{Y}_1$ of primary body **294** and is integrated second time to determine position Y_1 of primary body **294**. A phase angle ϕ_1 of primary body **294** is used to determine the external force U_1, which is applied to ducted fans **282** to primary body **294**.

In another embodiment, sensor **290** is a rate gyro mounted to each individual leg and used to trigger each ducted fan **282** independently. A rate gyro signal is pseudo integrated to determine the angular position θ of the thigh **172**. A phase angle ϕ is determined based on angular velocity $\dot{\theta}$ and angular position θ. A function of phase angle ϕ is used to trigger ducted fans **282**. In one embodiment, the sine of phase angle ϕ, as shown in equation (4), is used to trigger an individual ducted fan **282**. The sine of phase angle ϕ can be used to create a signal that varies between -1 and 1. The signal or -1 or 1 is used as a trigger for actuator **292** to oscillate ducted fans **282**.

A phase lock in amplifier or a phase locked loop is used to synchronize a sine generator from a signal from sensor **290**. A phase shift, delay, advance, change in amplitude, or change in sine is used to determine the desired airflow direction of ducted fans **282**. By using the sine of phase angle ϕ to trigger actuators **292**, the energy of phase oscillating system **280** remains bounded and stable. In another embodiment, the tangent of phase angle ϕ is the function used to trigger actuators **292**. By using the tangent of phase angle ϕ to trigger actuators **292**, the energy of phase oscillating system **280** remains bounded and stable. In yet another embodiment, the cosine of phase angle ϕ is the function used to determine trigger actuators **292**. Cosine of phase angle ϕ provides a damping system and reduces the energy of phase oscillating system **280**. Other functions, including arctangent, arcsine, arccosine, or another function of phase angle ϕ can be used to trigger actuators **292**.

Actuator **292** drives ducted fans **282**. Ducted fans **282** rotate to provide an oscillating external force. In one embodiment, actuator **292** orients the direction of ducted fans **282** or the direction of airflow for ducted fans **282**. Phase oscillating system **280** adjusts the direction of airflow for ducted fans **282** based on the gait of user **10**. In one embodiment, ducted fans are powered by brushless DC motors to create an external, horizontal force at torso **12** of user **10** to enhance running speed. The external force provided by ducted fans **282** increases the horizontal ground reaction force to increase the forward force and propulsion power to overcome drag and rolling friction at the ground. Additionally, the external force is turned off or redirected during the stance phase of gait to reduce the braking forces.

FIG. **7b** shows phase oscillating system **280** with ducted fans **282** rotated with respect to vertical. Ducted fans **282** can be aimed in any direction to provide external force U_1. In one embodiment, external force U_1 has vertical U_y and horizontal external force U_x components. An external horizontal force

U_x is provided to aid the runner at a magnitude of ten percent of body weight. An external horizontal force U_x is added to create a propulsive power to the user's gait. In one embodiment, phase oscillating system 280 is a jetpack that includes two ducted fans 282 that create a propulsive force of up to 45 Newtons (N) each. In one embodiment, external force U_1 is angled at 30 degrees when ducted fans 282 are positioned. A 30 degree angle provides force upwards or downwards in a vertical direction as well as a propulsive force in the horizontal direction. The external force U_1 oscillates direction according to the gait of user 10. In another embodiment, the external force U_1 is directed horizontally forward and backward to increase propulsive force during push off and enhance braking as the foot strikes the ground. In another embodiment, the external force U_1 is redirected up and down to enhance the up and down motion of torso 12 of user 10 during running. In another embodiment, the external force U_1 is directed horizontally to aid push-off, and no external force U_1 is applied during the swing phase of gait or when the foot strikes the ground. In another embodiment, the external force U_1 is directed horizontally during the push-off phase and is directed vertically as the foot strikes the ground to reduce the impact force of the foot strike.

Phase oscillating system 280 enhances human motion and reduces the metabolic cost of motion. Phase oscillating system 280 assists different speeds of motion, because a continuous control signal is generated and used as a triggering mechanism. For example, phase oscillating system 280 smoothly transitions from walking to running and back to walking. Phase oscillating system 280 provides a bounded energy and works for linear and rotary systems. Alternatively, phase oscillating system 280 provides a damping of energy to hinder motion, which is useful in exercise or training applications and during downhill walking and running.

The phase oscillating systems described herein provide the advantage of adding or subtracting energy when walking, jogging, running, carrying loads, climbing stairs, slopes, or hills, or reducing energy when walking down stairs or hills. The phase oscillating systems are also used to increase, maintain, or decrease vibrations in cars, airplanes, or appliances. The phase oscillating systems are also used as mechanical amplifiers to increase the energy harvested by energy harvesting devices. The phase oscillating systems are also used to alter the motion of a load being carried.

FIGS. 8a-8d show a phase oscillating system worn on an arm of a user. FIG. 8a shows a phase oscillating system 300 worn on arm 302 of user 10. Phase oscillating system 300 senses motion of arm 302 and responds by adding a negative or a positive external force. Phase oscillating system 300 is a device that oscillates a secondary mass, which applies an external force to a primary body. Arm 302 is the primary body 304 in phase oscillating system 300. User 10 wears phase oscillating system 300, or phase oscillating system 300 is coupled to the user by an attachment system 306. In one embodiment, attachment system 306 secures phase oscillating system 300 to arm 302 of user 10. In another embodiment, attachment system 306 includes straps, which secure phase oscillating system 300 to an upper limb 16 or a lower limb 14 of user 10. In yet another embodiment, phase oscillating system 300 is coupled to an exoskeleton or frame, which is coupled to user 10 or worn by user 10. In another embodiment, attachment system 306 is a protective wrist support. Attachment system 306 is a wearable, comfortable, exoskeleton apparatus that does not impede the normal functions of the hand and arm and can be put on and taken off quickly.

Phase oscillating system 300 is incorporated into a battering ram device 310. A secondary body 312 is attached to primary body 304 to enhance the motion of primary body 304. Secondary body 312 moves forward to increase the impact force, or to slow the effective swing down such that the human muscles can more efficiently add energy to battering ram device 310. Secondary body 312 moves backward at impact to increase follow-through force. Secondary body 312 is oscillated back and forth to assist in movement and increase hitting frequency. The proper timing of oscillation is based on a phase angle method or a phase locked loop method. Secondary body 312 is moved to change the center of gravity of battering ram device 310 to make the device easier to swing. Battering ram device 310 is attached to arm 302 to create a punching device. In another embodiment, battering ram device 310 is attached to a leg to create a kicking device.

Battering ram device 310 increases the maximum punching force and speed of the human hand. When striking a target, the device accelerates secondary body 312 effectively adding kinetic energy to the first or arm 302. The device can be controlled in one of two modes for either high power punches or increased punching frequency. With battering ram device 310, a soldier can now have the ability to punch very rapidly in hand-to-hand combat or punch through walls, doors, or other debris.

As arm 302 is moved in a manner consistent with punching, the device activates, accelerating secondary body 312 to produce a greater force at impact plate 314 than can be produced by user 10 without battering ram device 310. Secondary body 312 can be accelerated in both directions depending upon the device mode, either utilizing the forces required to accelerate secondary body 312 or the forces created as secondary body 312 collides with end stops within battering ram device 310.

As user 10 begins to punch, controller 324 monitors the movement of primary body 304 using an accelerometer to determine the type of punch intended by user 10, high force single punch or an enhanced force at a high frequency for repetitive punches. In the high force mode, secondary body 312 accelerates and collides with enclosure 330. The momentum secondary body 312 is transferred through impact plate 314 to the target object. Immediately after impact, secondary body 312 is accelerated backward causing a forward force against the target increasing the duration of the hit creating an amplified follow-through punch. In the high frequency mode, the motion of secondary body 312 is anti-phase with the motion of the arm 302. As the arm moves forward, secondary body 312 moves backward increasing the forward velocity thus enhancing impact force. As the arm moves backward, secondary body 312 moves forward increasing the arm's backward velocity such that high frequency, repetitive punching is possible.

FIG. 8b shows a schematic representation of phase oscillating system 300. Phase oscillating system 300 includes sensor 320, actuator 322, and controller 324. Sensor 320 is an accelerometer, vibrometer, rate gyro, potentiometer, inclinometer, global positioning system, or other sensor. Sensor 320 measures a physical state of a primary body 304. The physical state measurement may be linear position, linear velocity, linear acceleration, angular position, rotational or angular velocity, rotational or angular acceleration, or other state measurement. Controller 324 is coupled to sensor 320 and actuator 322. Controller 324 receives and processes the physical state measurement from sensor 320. Based on the physical state measurement from sensor 320, controller 324 triggers actuator 322 to move secondary body 312. Actuator 322 drives the oscillations of secondary body 312. Actuator 322 may include a linear actuator, pneumatic actuator, hydraulic actuator, electromagnetic actuator, or other suitable motor. Actuator 322 quickly accelerates secondary body 312

by either stored high pressure gas or a combustion chamber, a lightweight frame utilizing composites and or alloys, valves or firing pin mechanism controlled by a microprocessor, and an impact plate to transfer kinetic energy to a target.

The movement of secondary body 312 produces an external force, which acts on primary body 304. Secondary body 312 may comprise any type of object, including a weight or combination of fluids of different densities. In one embodiment, secondary body 312 is an eccentric mass. Secondary body 312 is coupled to primary body 304 at any position along primary body 304.

FIG. 8c shows a schematic representation of phase oscillating system 300. In one embodiment, sensor 320 is an accelerometer attached to primary body 304 to measure acceleration $\ddot{Y}_1$ of primary body 304. The acceleration $\ddot{Y}_1$ is integrated once to determine velocity $\dot{Y}_1$, and a second time to determine position Y of primary body 304. A phase angle ϕ may be determined by taking the arc tangent of velocity $\dot{Y}_1$ versus position Y or acceleration $\ddot{Y}_1$ versus velocity $\dot{Y}_1$. A function of the phase angle ϕ determines the desired external force to be applied to primary body 304. For example, the desired external force can be determined by using the functions shown in equations (4), (5), (6), (7), or (8). In one embodiment, phase angle ϕ is a kinematic phase angle. A phase lock in amplifier or a phase locked loop may be used to synchronize a sine generator or pattern from a signal from sensor 320. A phase shift, delay, advance, change in amplitude, or change in sine may be used in determining the desired external force.

The oscillation or movement of secondary body 312 produces external force U_1 by pulling on or pushing against primary body 304. Secondary body 312 is oscillated based on the phase angle ϕ_1 of primary body 304. By oscillating secondary body 312 in phase with respect to primary body 304, energy is added to the motion of primary body 304. By oscillating secondary body 312 out of phase with respect to primary body 304, energy is subtracted from the motion of primary body 304.

The desired external force U_1 may be divided by the mass of secondary body 312 to determine a desired acceleration $\ddot{Y}_2$ for secondary body 312. The desired acceleration $\ddot{Y}_2$ is integrated once to determine a velocity profile $\dot{Y}_2$. The desired acceleration $\ddot{Y}_2$ is integrated twice to determine a desired position Y_2 for secondary body 312. Secondary body 312 is oscillated based on the desired position profile Y_2 or velocity profile $\dot{Y}_2$. The movement of secondary body 312 provides a reaction force by pulling or pushing against primary body 304 or by hitting the end of enclosure 330.

Secondary body 312 is oscillated by a number of different methods, for example, a linear actuator, a pneumatic actuator, a hydraulic actuator, or other motor. By oscillating secondary body 312 based on phase angle ϕ of primary body, energy is applied to the motion of primary body 304. Such energy may be used to decrease the energy necessary to be exerted by primary body 304 to move with a certain speed or acceleration.

As secondary body 312 oscillates, the force applied on primary body 304 by secondary body 312 alternates between a positive and negative force with respect to the direction of movement of primary body 304. While secondary body 312 applies a positive force on primary body 304 and primary body 304 has a positive velocity, the positive force enhances the movement of primary body 304 by applying positive power. While secondary body 312 applies a negative force on primary body 304 and primary body 304 has a negative velocity, the negative force enhances the movement of primary body 304 by applying positive power. While secondary body

312 applies a positive force on primary body 304 and primary body 304 has a negative velocity, the positive force resists the movement of primary body 304 by applying negative power. While secondary body 312 applies a negative force on primary body 312 and primary body 312 has a positive velocity, the negative force resists the movement of primary body 304 by applying negative power. By applying positive power at the correct times based on phase angle ϕ, the net effect can be to assist movement. By applying negative power at the correct times based on the negative of phase angle ϕ, the net effect can be to resist movement.

Phase oscillating system 300 provide advantages by making it easier for user 10 to swing battering ram device 310. The hitting frequency, the force at impact, and the follow-through force can be increased. The motion of the center of mass can be enhanced to ease the use and increase the human muscle efficiency.

FIG. 8d shows an alternative phase oscillating system 340. Phase oscillating system 340 includes an optional suspension system 342 coupled to secondary body 312. Suspension system 342 may include a plurality of spring forces and damper forces. Suspension system 342 may include springs, air springs, air pistons, dampers, and bumpers. In one embodiment, suspension system 342 includes a compliant element such as a helical or coil spring.

Secondary body 312 is coupled to primary body 304 by a spring 342 or similar mechanism that allows secondary body 312 to oscillate with respect to primary body 304. In one embodiment, the vector of motion or actuation of secondary body 312 is not parallel to the vector of motion of primary body 304.

The desired external force U_1 is applied on primary body 304 by secondary body 312. Secondary body 312 may oscillate such that secondary body 312 alternately applies positive and negative forces on primary body 304. By applying the positive and negative forces at specific timing, the net effect enhances or inhibits movement of primary body 304. In one embodiment, secondary body 312 moves in simple harmonic oscillation. Secondary body 312 may move linearly, circularly, elliptically, or in any other pattern.

In one embodiment, the movement of secondary body 312 provides a reaction force by pulling or pushing against primary body 304 or by hitting the end of enclosure 330. When secondary body 312 impacts enclosure 330 mounted on primary body 304, the impact force is increased. In another embodiment, secondary mass 312 moves in an opposite direction to primary body 304 to increase the follow-through force.

Secondary body 312 moves in an opposing direction or out of phase with respect to primary body 304, thereby increasing or assisting oscillatory motion of primary body 304 relative to the ground and increase hitting frequency. Alternatively, secondary body 312 moves the same direction as primary body 304 in phase with primary body 304, thereby inhibiting oscillatory motion of primary body 304 relative to the ground to aid in dampening the recoil force.

FIGS. 9a-9d show graphical representations of the operation of a phase oscillating system. FIG. 9a shows phase oscillating systems as the system oscillates back and forth according to the sine of phase angle ϕ. The sine of phase angle ϕ for phase oscillating systems is shown graphically as line 400. In one embodiment, mass m of a primary body is 1 kilogram (kg), spring constant k is 200 Newtons per meter (N/m), damping b is 0.6 Newton-seconds per meter (Ns/m), constant c is 0.6, initial velocity is 1.2 meters per second (m/s), and an initial position is at the ground, or 0 meters (m). In FIG. 9a, line 400 represents a phase oscillating system that provides

positive power to a primary body. By using the sine of phase angle ϕ_1 to determine external force U_1, the energy of the phase oscillating system remains bounded and stable.

FIG. 9b shows a phase plot that demonstrates a limit cycle as the system position oscillates back and forth. In FIG. 9b, line 410 represents a phase oscillating system that provides positive power to a primary body. By using the sine of phase angle ϕ_1 to determine external force U_1, the energy of the phase oscillating system remains bounded and stable. The direction of the cycle in the phase plot of FIG. 9b is shown by arrow 412. In one embodiment, mass m of a primary body is 1 kg, spring constant k is 200 N/m, damping b is 0.6 Ns/m, and constant c is 0.6, initial velocity is 1.2 m/s, and an initial position is at the ground, or 0 m.

FIG. 9c shows the phase oscillating system as the system damps to zero. In FIG. 9c, line 420 represents a phase oscillating system that provides negative power or damping to a primary body. In one embodiment, mass m of a primary body is 1 kg, spring constant k is 200 N/m, damping b is 0.6 Ns/m, and constant c is –0.6, initial velocity is 4 m/s, and an initial position is at the ground, or 0 m.

FIG. 9d shows a phase plot as the system position and velocity return back to zero. In FIG. 9d, line 430 represents a phase oscillating system that provides negative power or damping to a primary body. The direction of the cycle in the phase plot of FIG. 9d is shown by arrow 432. In one embodiment, mass m of a primary body is 1 kg, spring constant k is 200 N/m, damping b is 0.6 Ns/m, and constant c is –0.6, initial velocity is 4 m/s, and an initial position is at the ground, or 0 m.

While one or more embodiments of the present invention have been illustrated in detail, the skilled artisan will appreciate that modifications and adaptations to those embodiments may be made without departing from the scope of the present invention as set forth in the following claims.

What is claimed:

1. A method of making a movement assistance device, comprising:
providing a sensor;
measuring a physical state of a limb using the sensor;
determining a phase angle of the limb based on the physical state;
filtering the phase angle of the limb using a sine function;
coupling an actuator to the limb; and
triggering the actuator based on the phase angle of the limb to provide an oscillating force to assist movement of the limb.

2. The method of claim 1, further including:
providing a mass coupled to the limb and actuator; and
oscillating the mass using the actuator.

3. The method of claim 1, wherein measuring the physical state of the limb further includes measuring position, velocity, or acceleration of the limb.

4. The method of claim 1, further including synchronizing the actuator with the physical state using a phase lock in amplifier or a phase locked loop.

5. The method of claim 1, further including:
coupling a damper to the limb; and
harvesting energy from the damper, wherein the energy is produced by movement of the limb.

6. A method of making a phase oscillating device, comprising:
providing a sensor;
measuring a physical state of a primary body of a user using the sensor;
determining a phase angle of the primary body of the user based on the physical state;

filtering the phase angle of the primary body of the user; and
triggering an actuator based on the phase angle of the primary body of the user to oscillate a force or a torque applied to the primary body of the user.

7. The method of claim 6, further including:
coupling a secondary body to the primary body of the user; and
oscillating the secondary body using the actuator, the force or torque applied to the primary body of the user by the oscillating secondary body.

8. The method of claim 6, further including triggering the actuator in phase with a gait step of the primary body of the user.

9. The method of claim 6, further including enhancing or restricting movement of the primary body of the user with the force or torque.

10. The method of claim 6, wherein measuring the physical state of the primary body of the user further includes measuring position, velocity, or acceleration of the primary body of the user.

11. The method of claim 6, further including coupling a fan to the actuator, wherein the fan produces the force applied to the primary body of the user.

12. The method of claim 6, wherein the primary body of the user includes a limb of the user.

13. The method of claim 6, wherein the primary body of the user includes a torso of the user.

14. The method of claim 6, further including measuring the physical state continuously to provide a continuous control signal for triggering the actuator.

15. The method of claim 6, further including determining the phase angle based on a function of acceleration and velocity of the primary body.

16. The method of claim 6, further including determining the phase angle based on a function of velocity and position of the primary body.

17. A phase oscillating device, comprising:
a primary body of a user;
a sensor coupled to the primary body of the user;
a controller coupled to the sensor to determine a phase angle of the primary body of the user; and
an actuator coupled to the controller to oscillate a signal to the actuator based on a trigonometric function of the phase angle of the primary body of the user.

18. The phase oscillating device of claim 17, further including a secondary body coupled to the actuator and primary body of the user.

19. The phase oscillating device of claim 18, wherein the actuator oscillates the secondary body to assist or restrict movement of the primary body of the user.

20. The phase oscillating device of claim 17, further including a fan coupled to the primary body of the user and actuator to apply an oscillating force to primary body of the user based on the signal to the actuator.

21. The phase oscillating device of claim 17, further including an exoskeleton structure coupled to the primary body of the user, controller, and actuator, the exoskeleton configured to fit onto the user.

22. A method of making a phase oscillating device, comprising:
providing a sensor;
measuring a physical state of a primary body of a user using the sensor;
determining a phase angle of the primary body of the user based on the physical state;
coupling an actuator to the primary body of the user; and

triggering the actuator based on a trigonometric function of the phase angle of the primary body of the user to provide a force or a torque to assist movement of the primary body of the user.

23. The method of claim **22**, wherein measuring the physical state of the primary body of the user further includes measuring position, velocity, or acceleration of the primary body of the user.

24. The method of claim **22**, further including synchronizing the actuator with the physical state using a phase lock in amplifier or a phase locked loop.

25. The method of claim **22**, wherein the primary body of the user includes a torso of the user.

26. The method of claim **22**, further including determining the force to assist movement of the primary body by filtering the phase angle using a sine function.

27. A method of making a phase oscillating device, comprising:

providing a sensor;

measuring a physical state of a primary body of a user using the sensor;

determining a phase angle of the primary body of the user based on the physical state;

filtering the phase angle using a trigonometric function;

producing a signal based on the filtered phase angle; and

controlling an actuator based on the signal.

28. The method of claim **27**, wherein the primary body of the user includes a limb of the user.

29. The method of claim **27**, further including determining the phase angle based on a function of acceleration and velocity of the primary body.

30. The method of claim **27**, further including determining the phase angle based on a function of velocity and position of the primary body.

31. The method of claim **27**, further including synchronizing the actuator with the physical state using a phase lock in amplifier or a phase locked loop.

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